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(54) **SYSTEMS AND METHODS FOR CURRENT SENSING**

7,075,287 B1 7/2006 Mangtani et al.
7,166,807 B2 1/2007 Gagnon et al.
7,259,545 B2 8/2007 Stauth et al.
7,476,816 B2 1/2009 Doogue et al.
7,518,354 B2 4/2009 Stauth et al.
(Continued)

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OTHER PUBLICATIONS

Allegro Datasheet ACS724 “Automotive-Grade, Galvanically Isolated Current Sensor IC With Common-Mode Field Rejection in a Small-Footprint SOIC8 Package”, Dec. 13, 2018, 33 pages.

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(Continued)

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(57) **ABSTRACT**

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Systems and methods described herein are directed towards differential current sensing a current sensor having two or more magnetic field sensing elements that are oriented to sense a magnetic field generated by a current through an external conductor in the same direction. The current sensor can be positioned such that at least one first magnetic field sensing element is vertically aligned with the external conductor and at least one second magnetic field sensing element is not vertically aligned with the external conductor. The magnetic field sensing elements may be spaced from each to measure a gradient field and can generate a magnetic field signal indicative of a distance between the respective magnetic field sensing element and the current carrying external conductor. A difference between the magnetic field signals can be determined that is indicative of the current through the external conductor.

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H01L 23/495 (2006.01)
G01R 33/00 (2006.01)

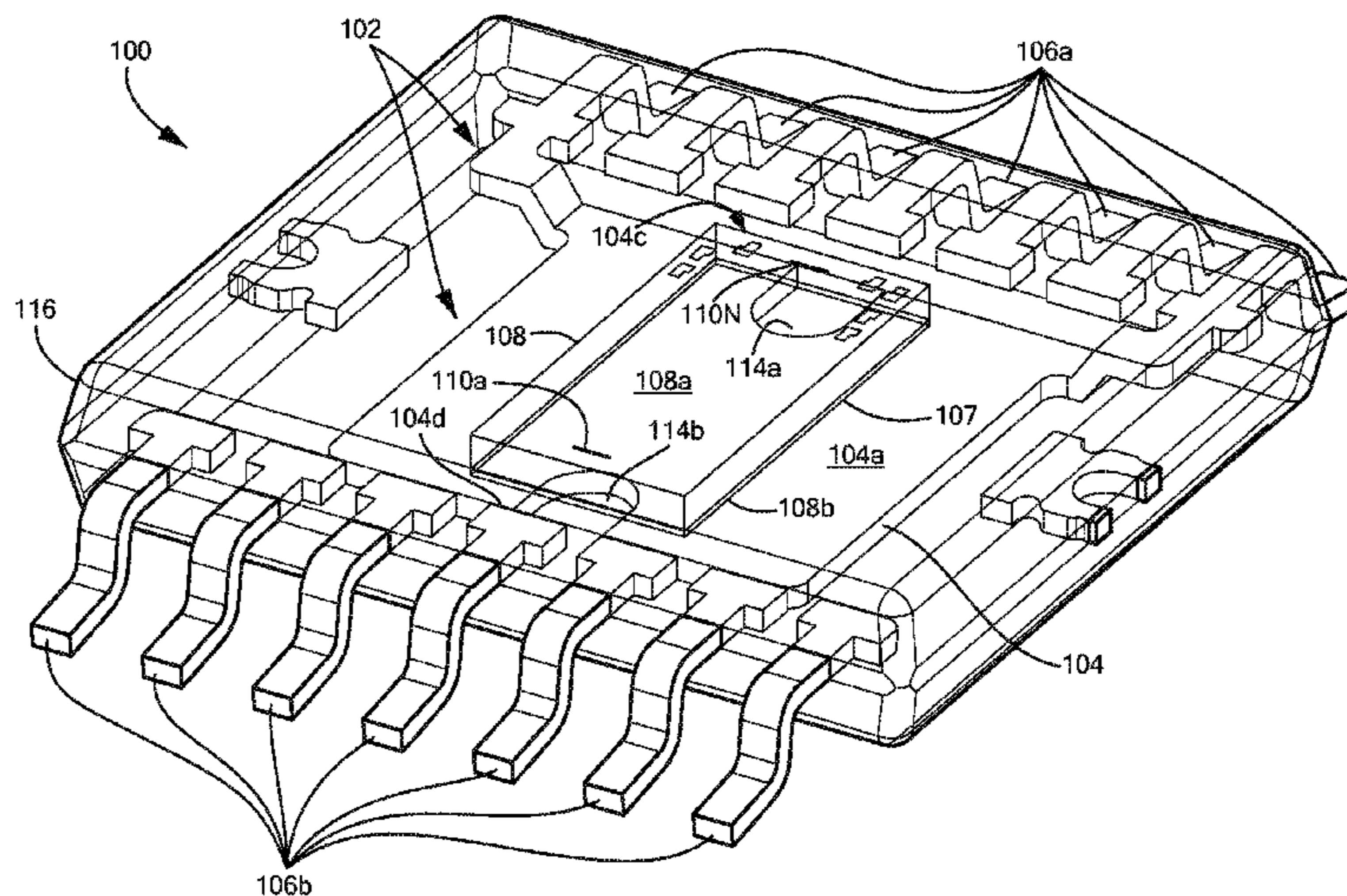
(52) **U.S. Cl.**
CPC *G01R 15/207* (2013.01)

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CPC ... G01R 15/207; G01R 15/202; G01R 15/205
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(56) **References Cited**
U.S. PATENT DOCUMENTS

6,356,068 B1 3/2002 Steiner et al.
6,995,315 B2 2/2006 Sharma et al.

28 Claims, 11 Drawing Sheets



(56)

References Cited

U.S. PATENT DOCUMENTS

7,598,601 B2 10/2009 Taylor et al.
7,709,754 B2 5/2010 Doogue et al.
7,746,056 B2 6/2010 Stauth et al.
7,816,905 B2 10/2010 Doogue et al.
8,080,994 B2 12/2011 Taylor et al.
9,081,041 B2* 7/2015 Friedrich G01R 15/207
9,190,606 B2 11/2015 Liu et al.
2006/0219436 A1* 10/2006 Taylor H01L 24/37
174/529
2007/0170533 A1* 7/2007 Doogue B82Y 25/00
257/422
2015/0022187 A1 1/2015 Taylor et al.

OTHER PUBLICATIONS

Melexis Datasheet MLX91206 “IMC-Hall® Current Sensor (Triaxis® Technology)”, Apr. 2016, 25 pages.
Sensitec datasheet CFS1000 “Integrated MagnetoResistive Current Sensor”, Apr. 25, 2016, 27 pages.

* cited by examiner

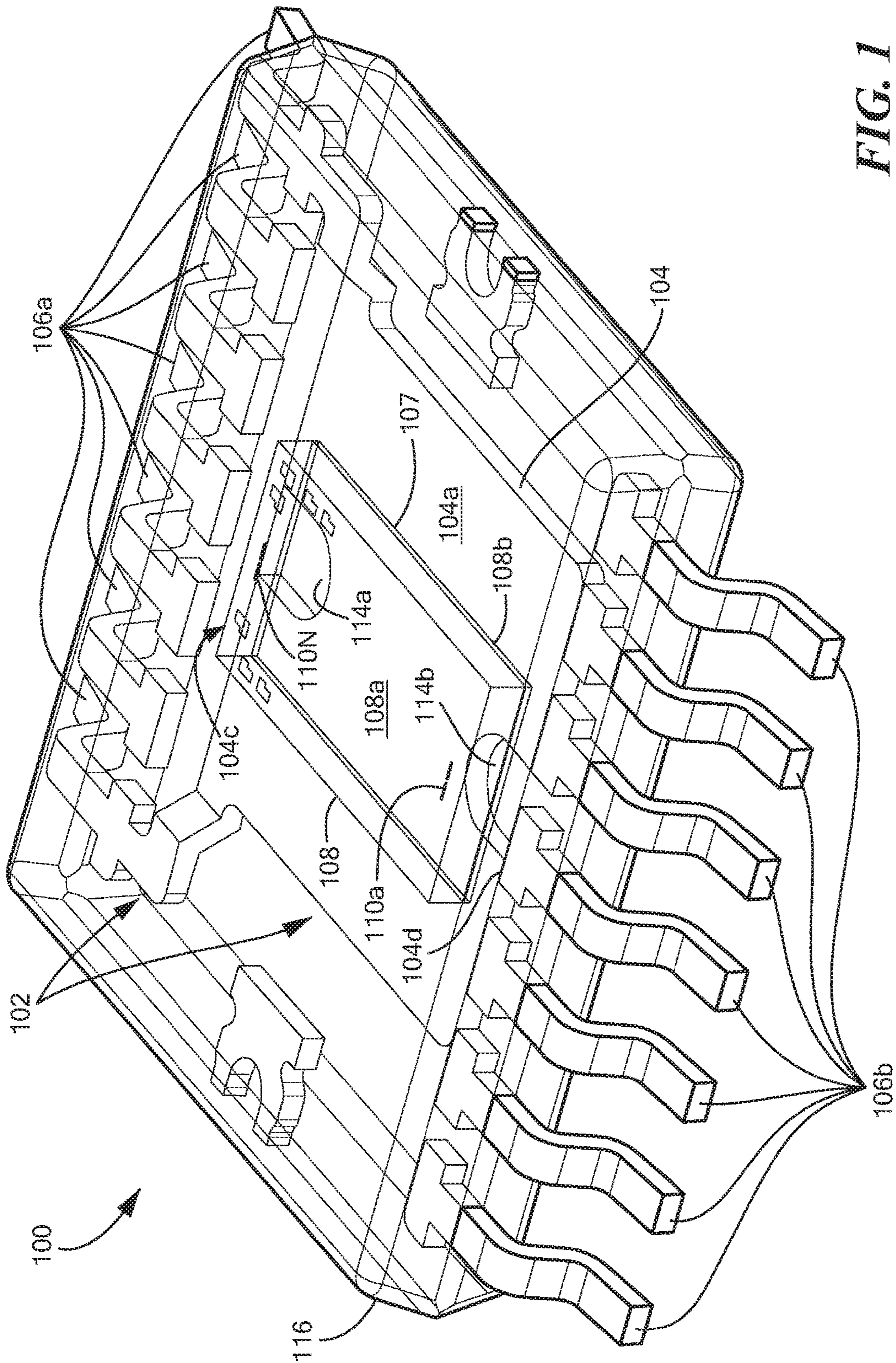


FIG. 1

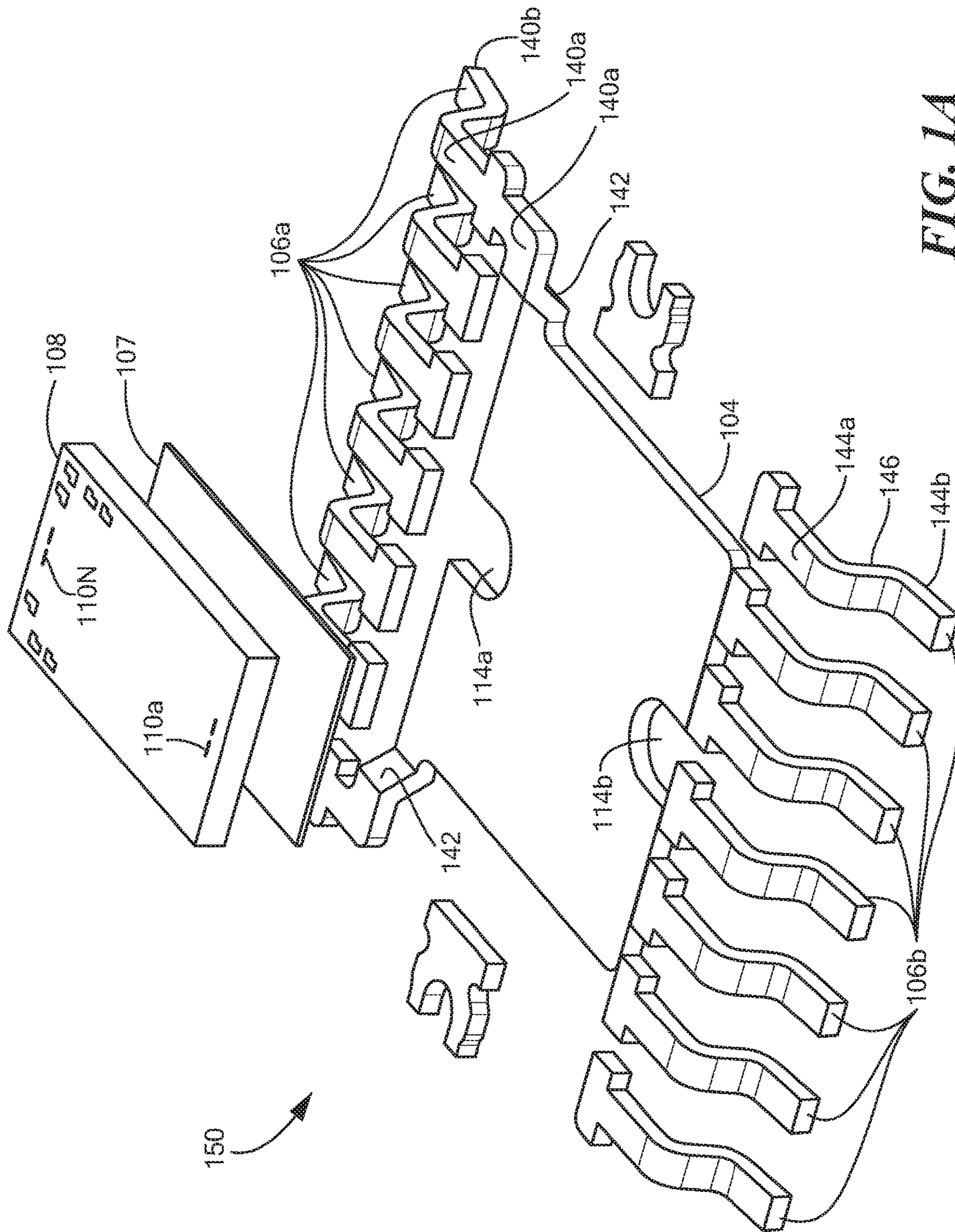


FIG. 1A

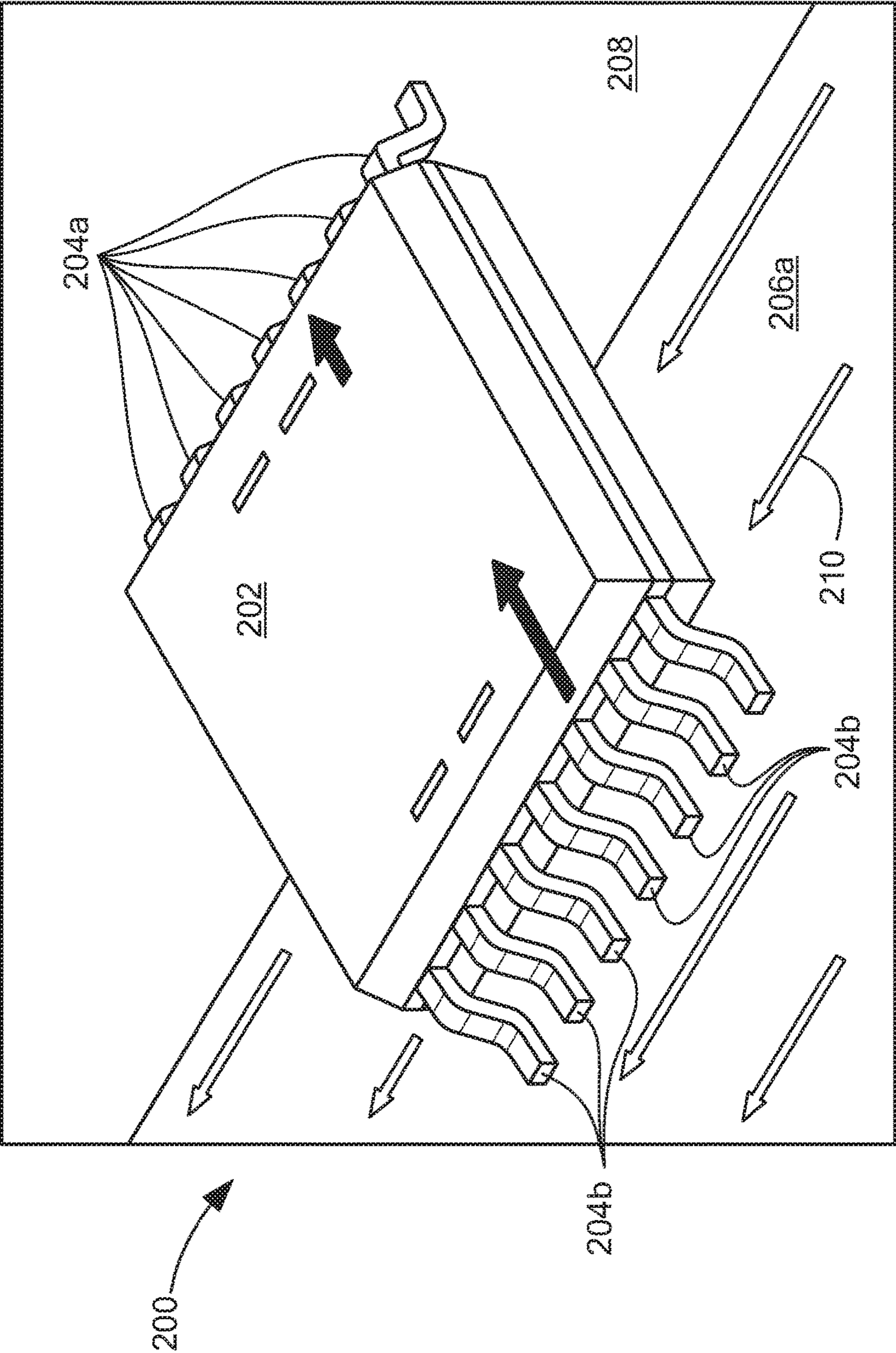


FIG. 2

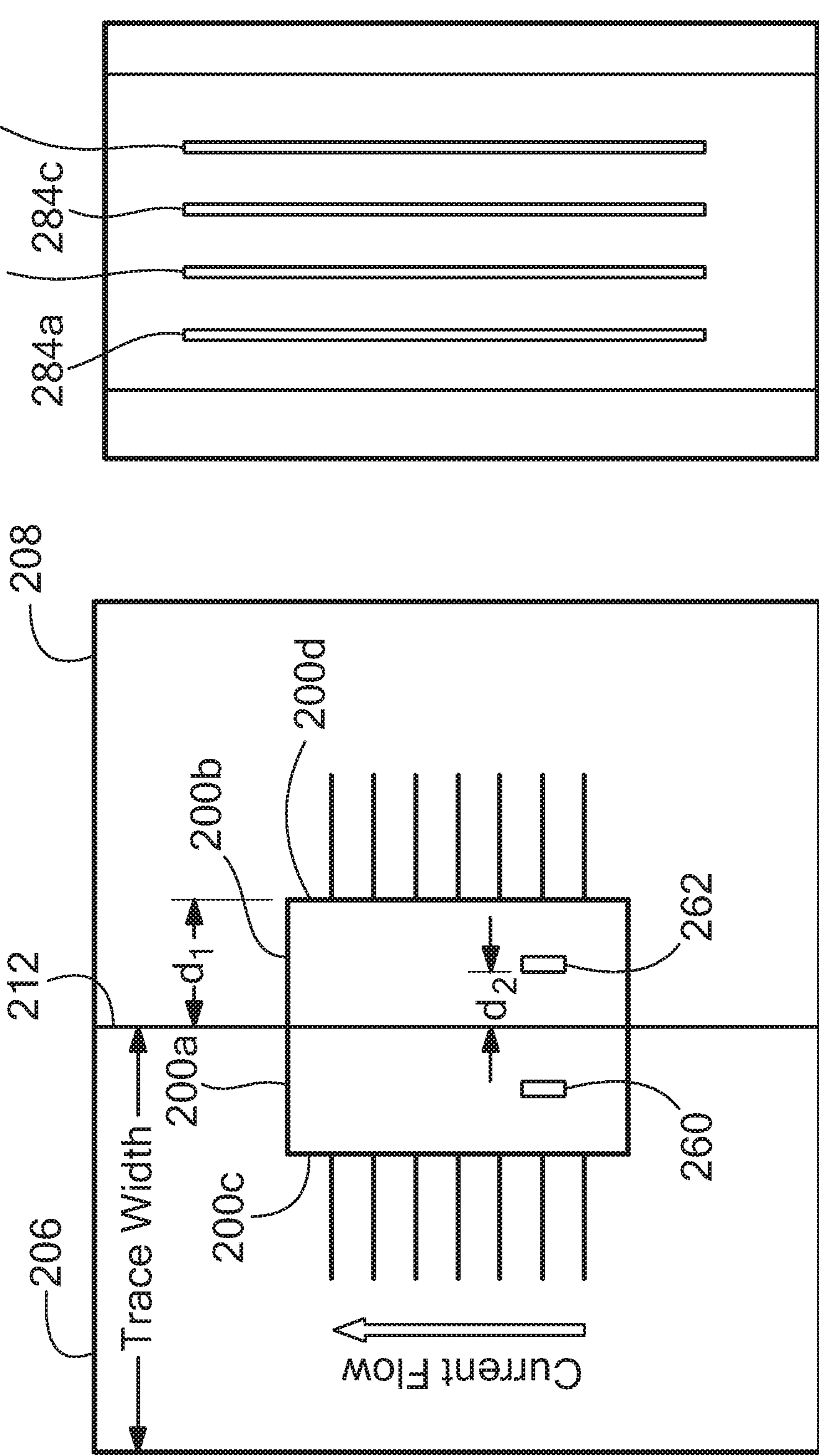


FIG. 2A

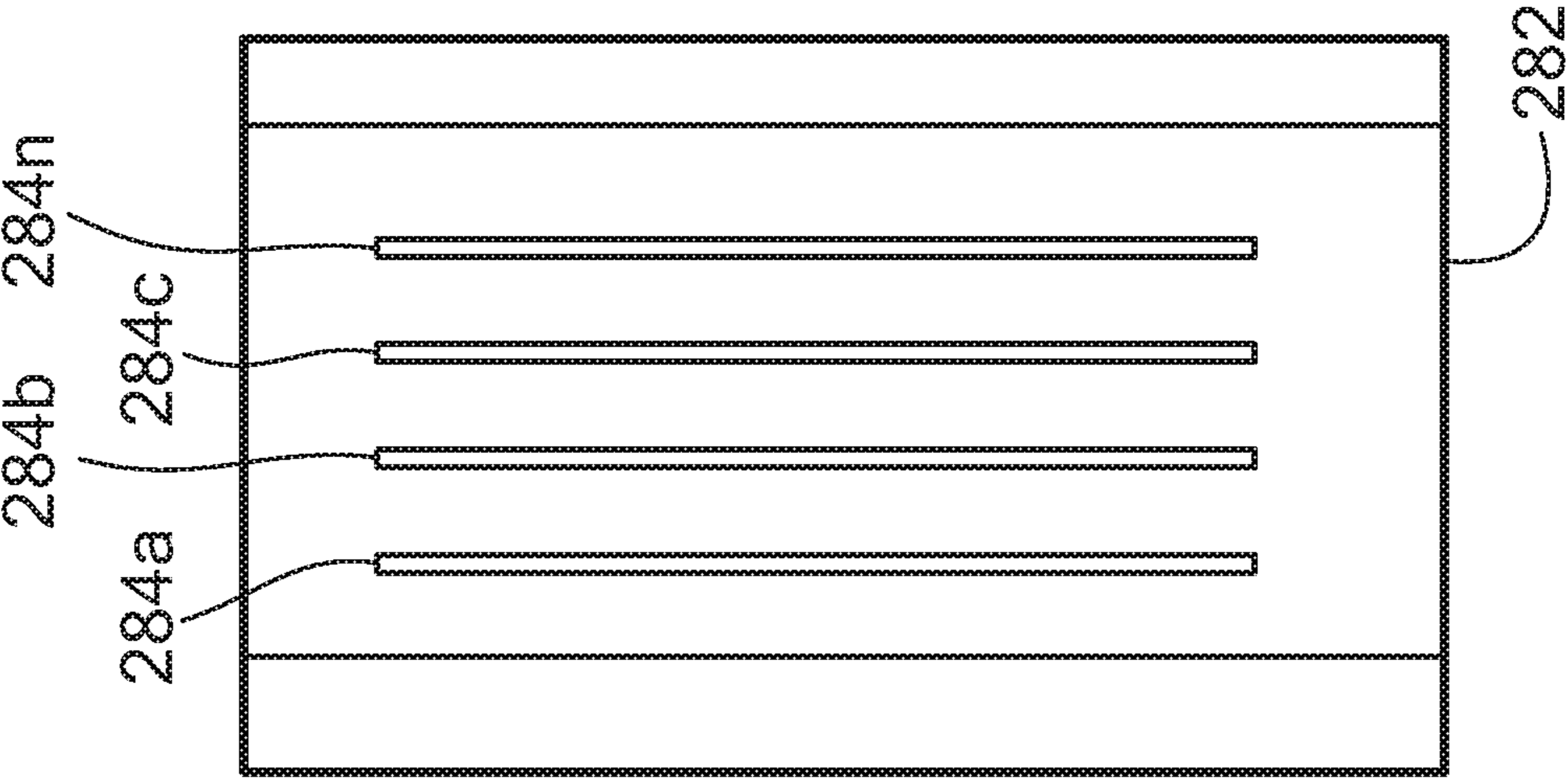


FIG. 2B

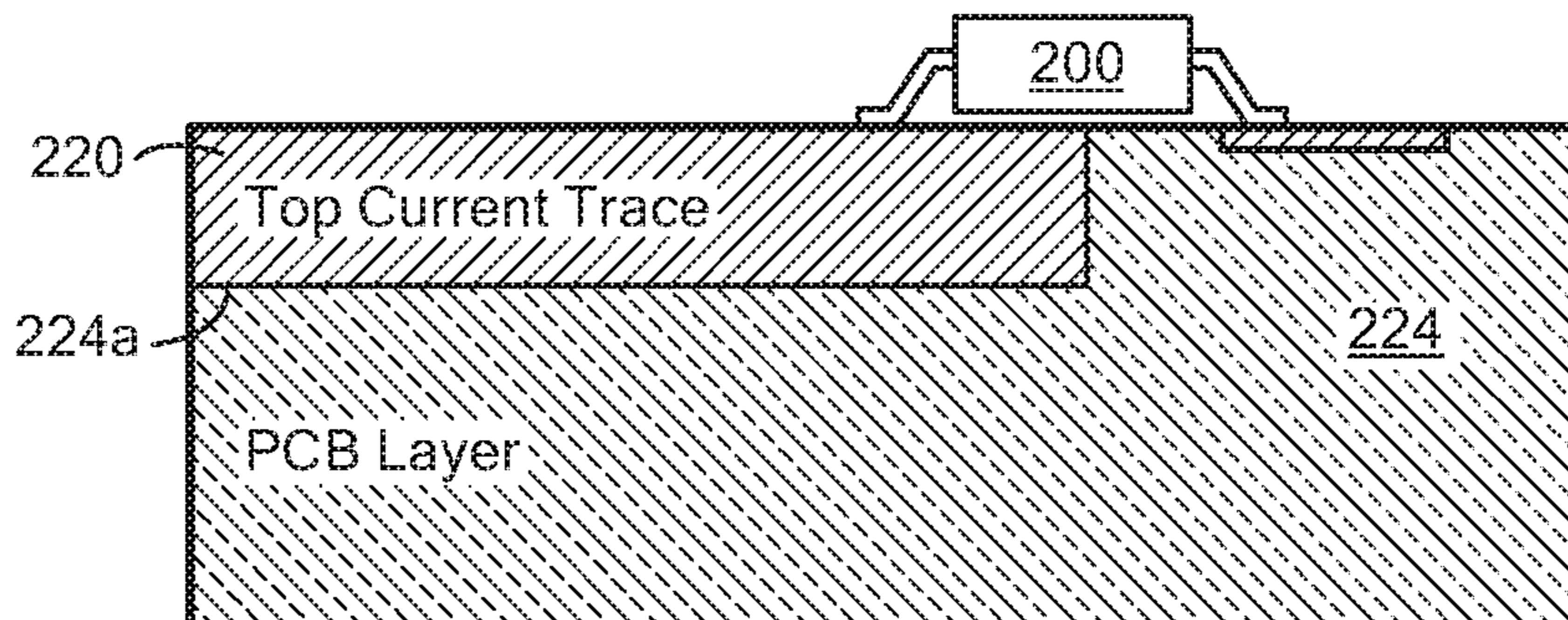


FIG. 2C

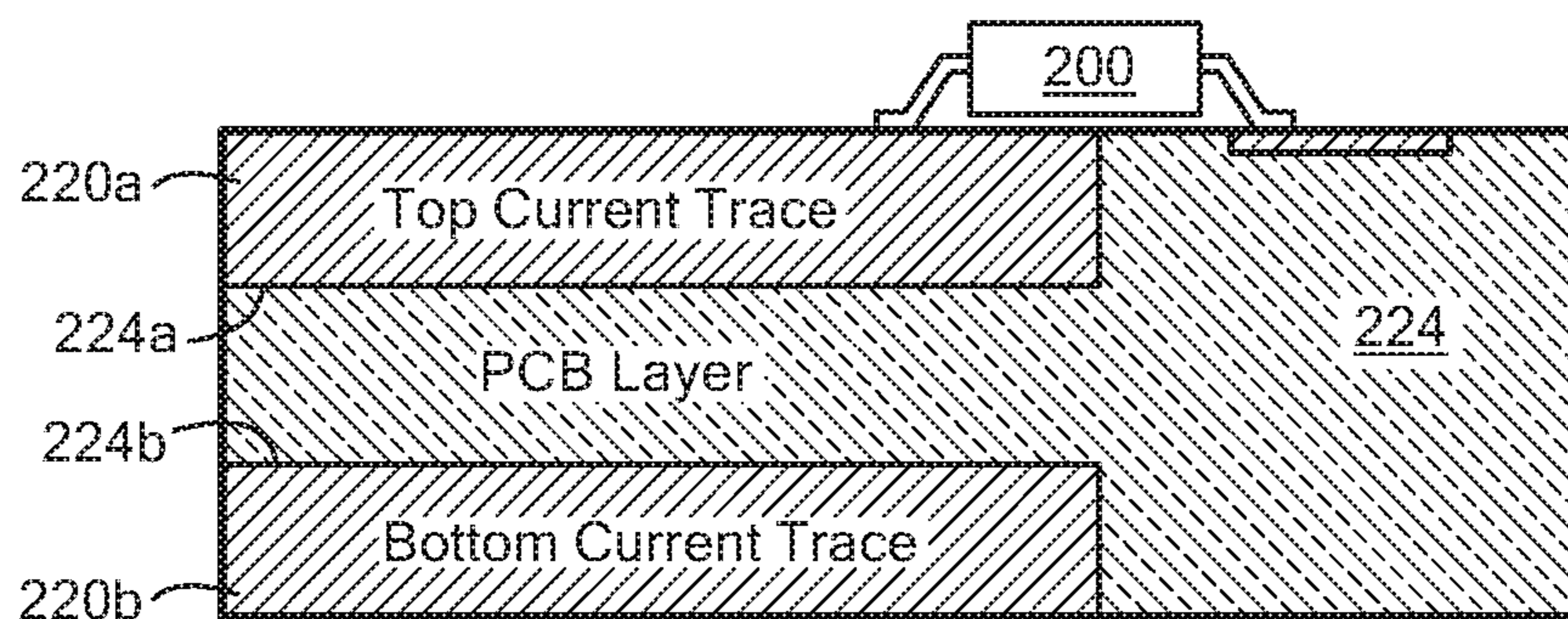


FIG. 2D

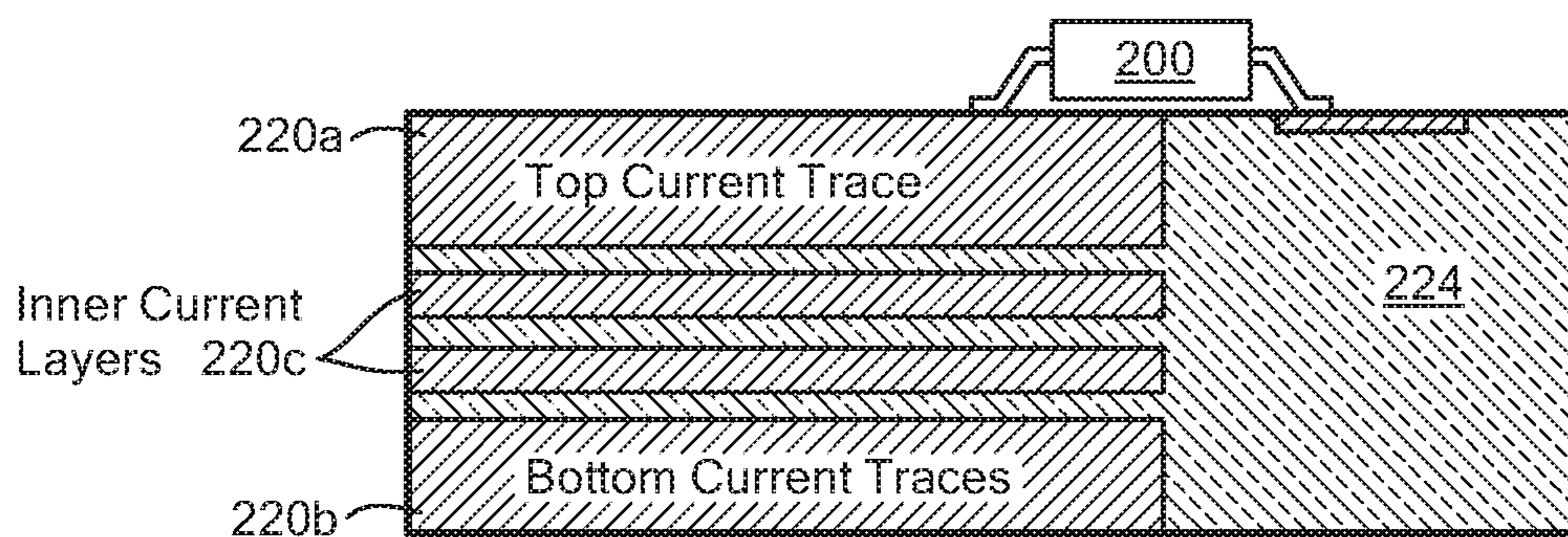


FIG. 2E

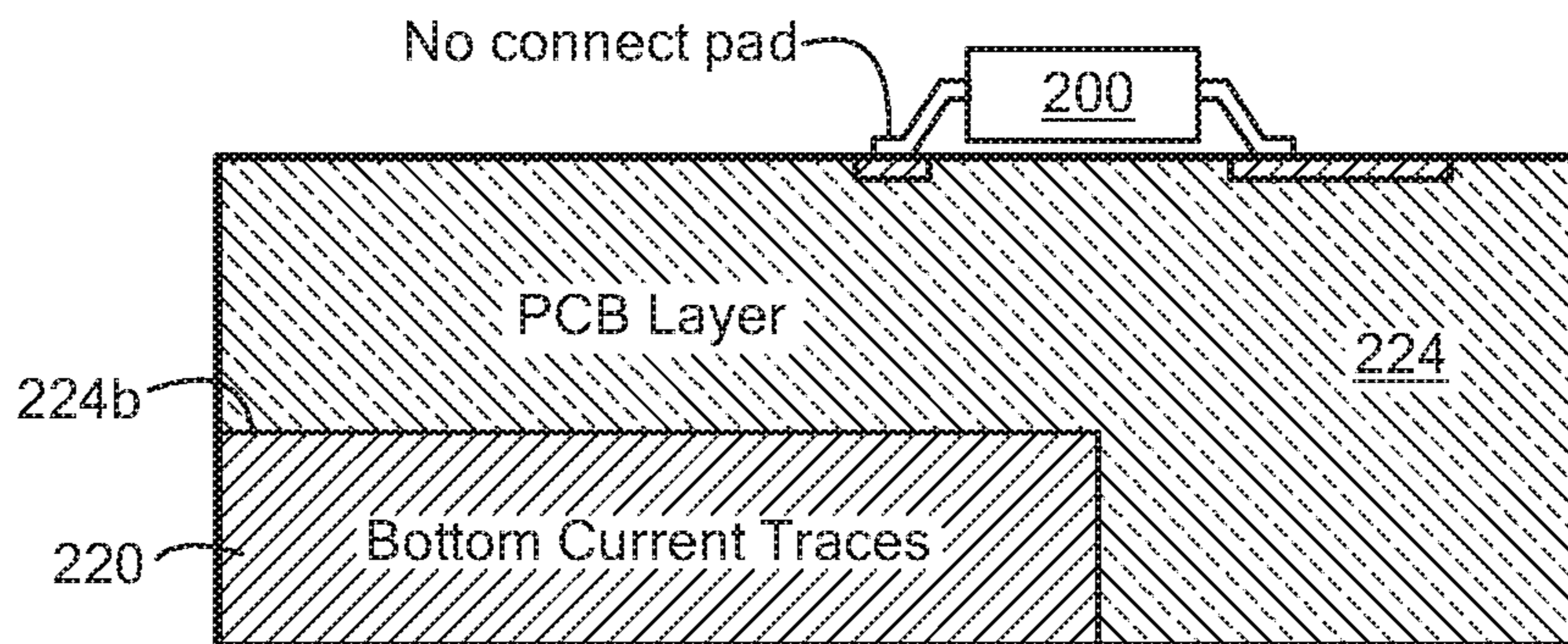


FIG. 2F

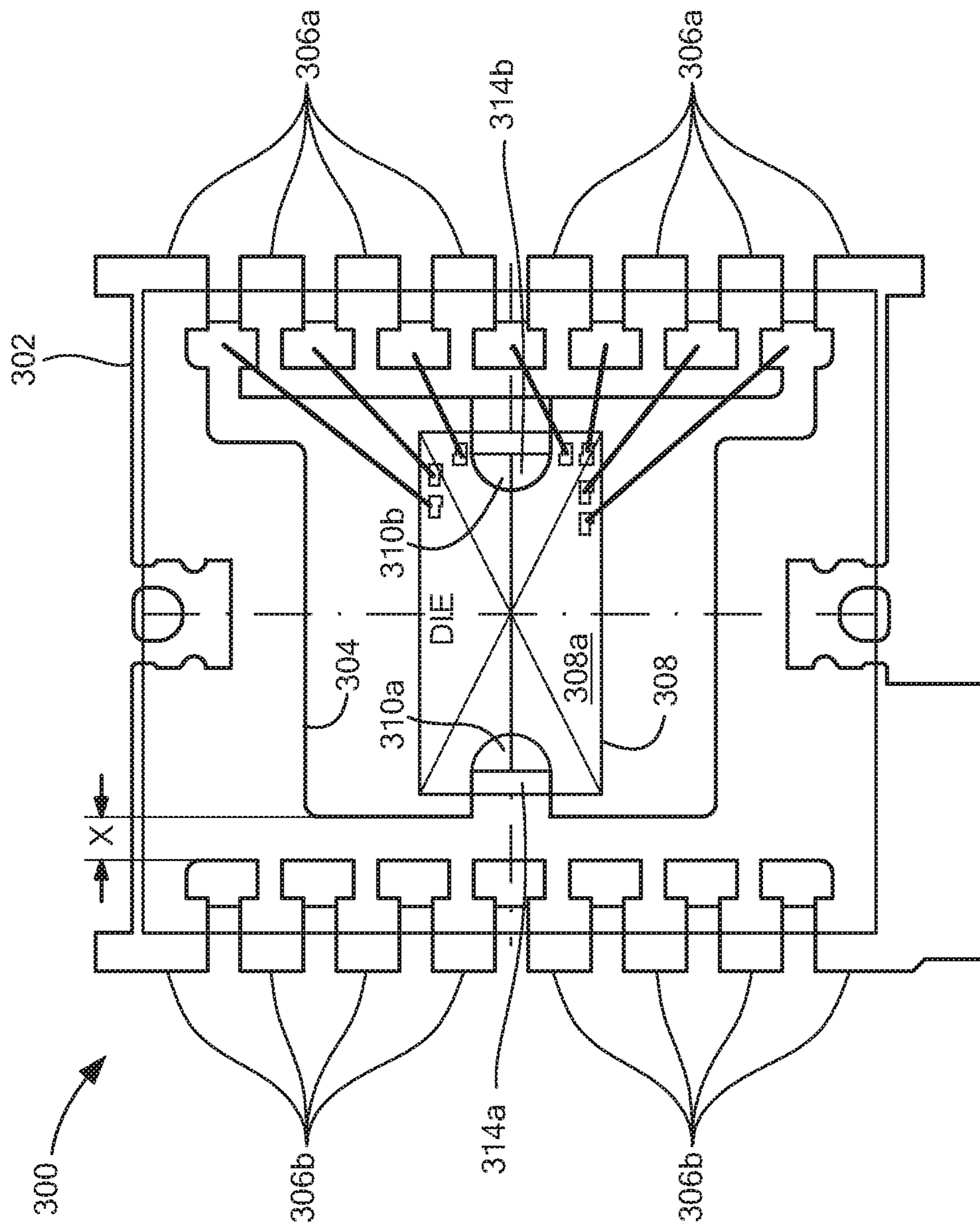


FIG. 3

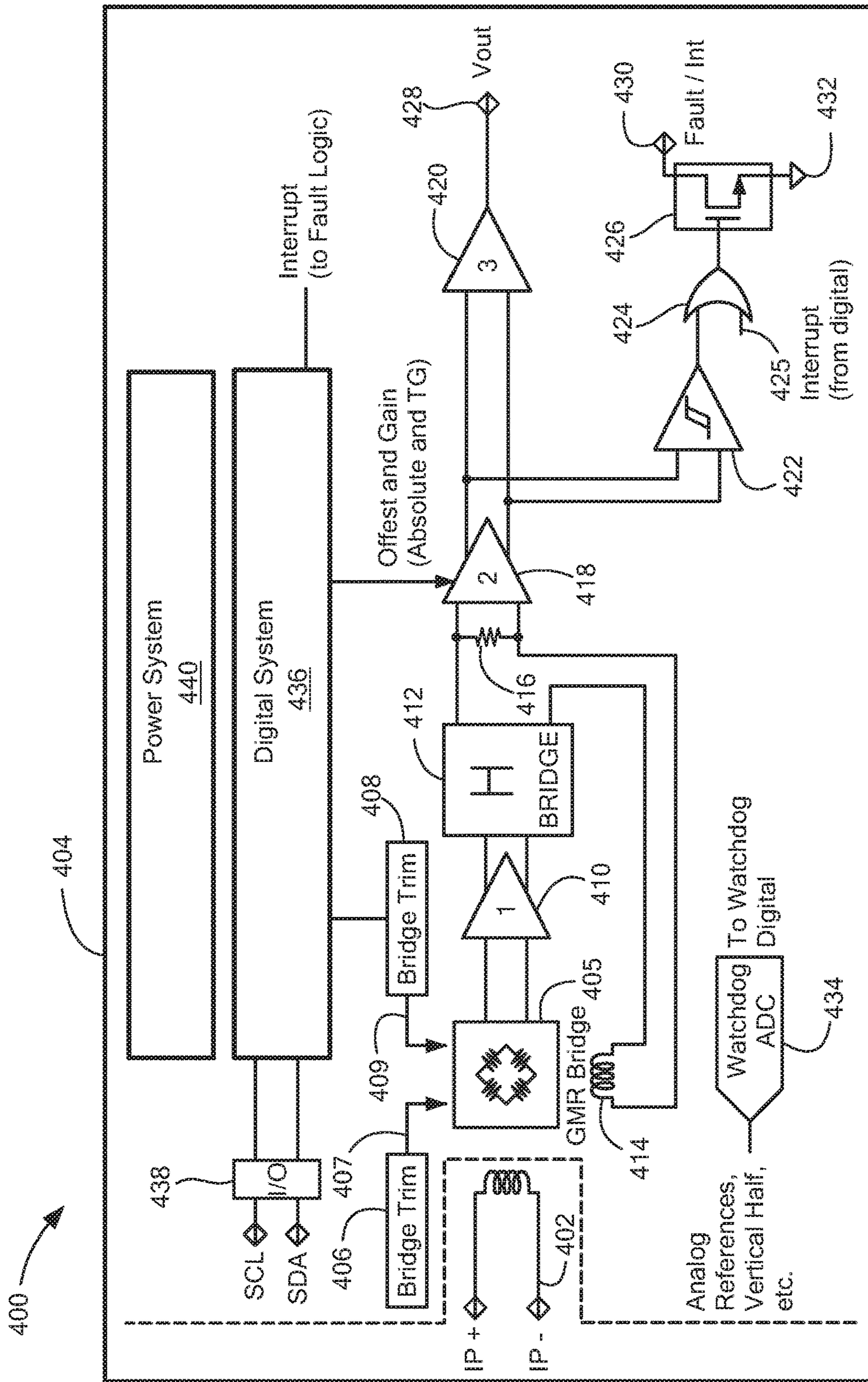


FIG. 4

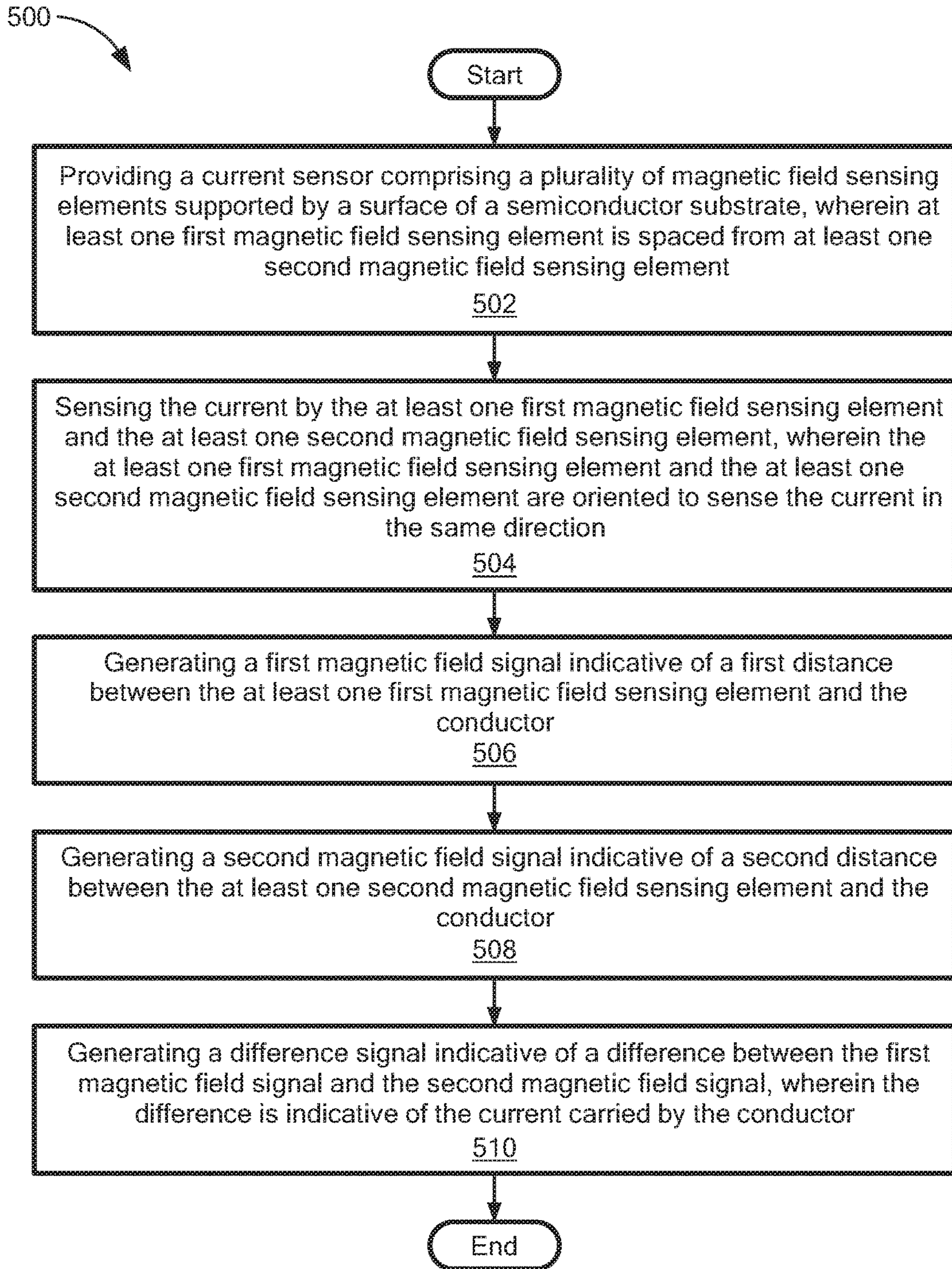
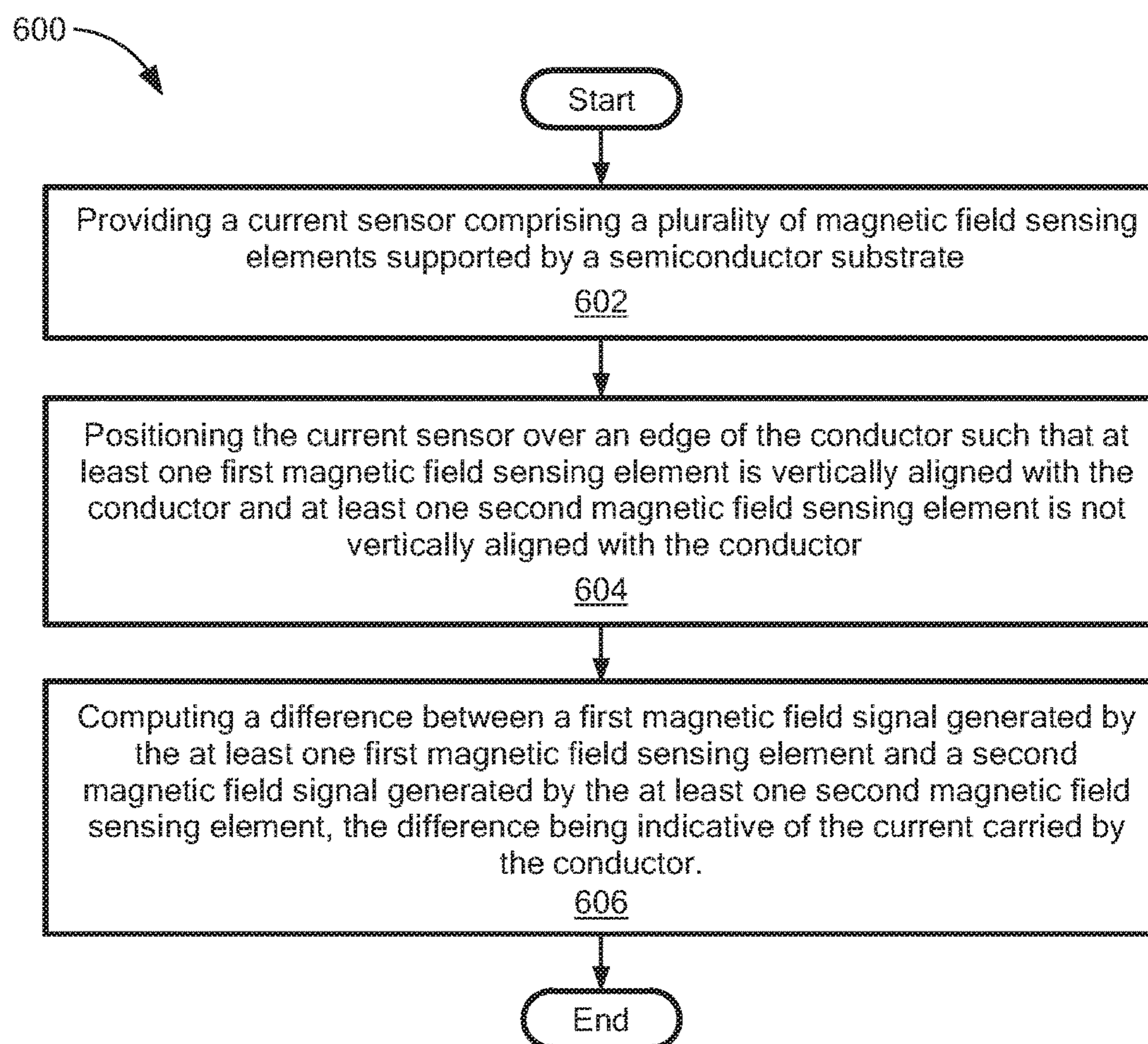


FIG. 5

**FIG. 6**

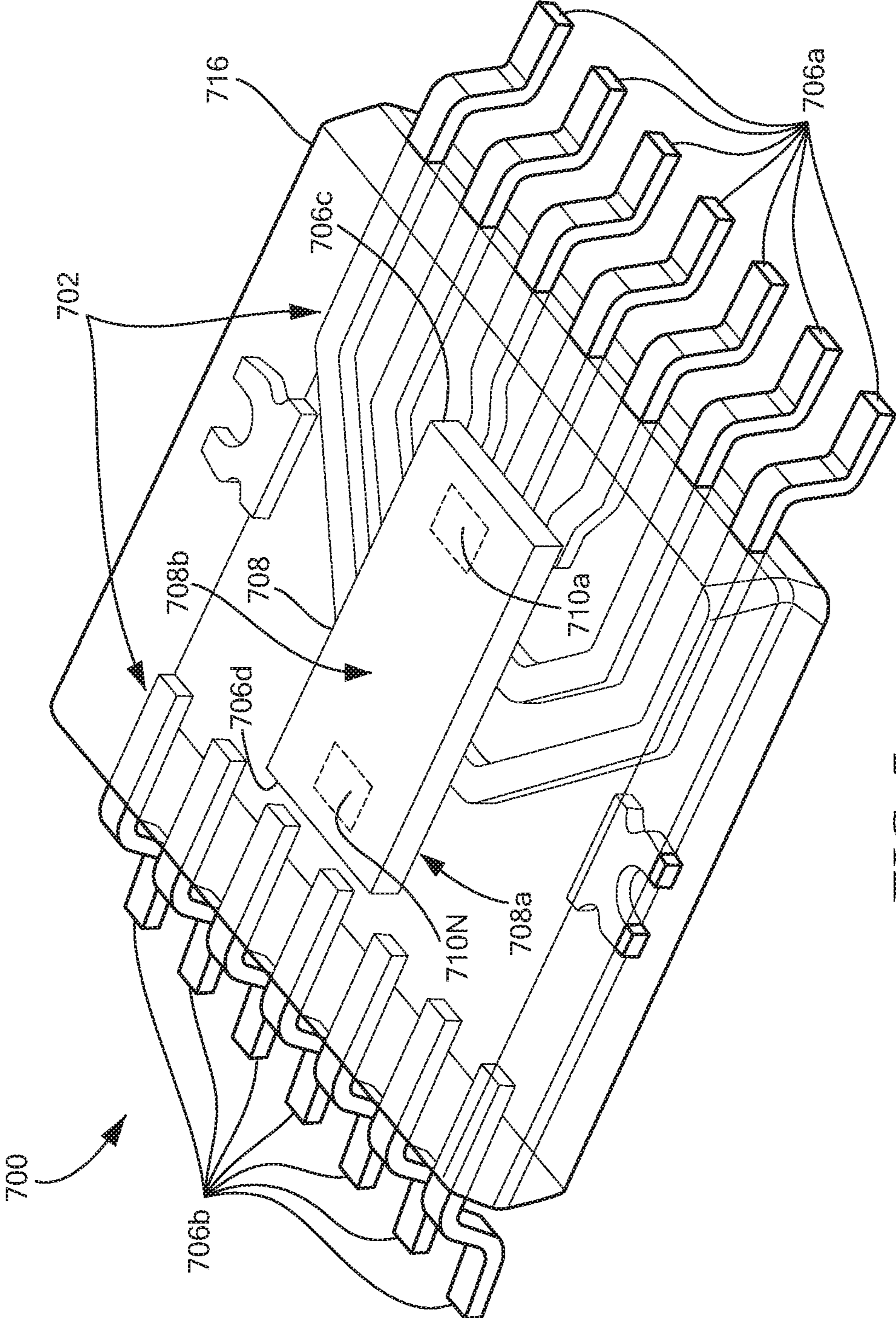


FIG. 7

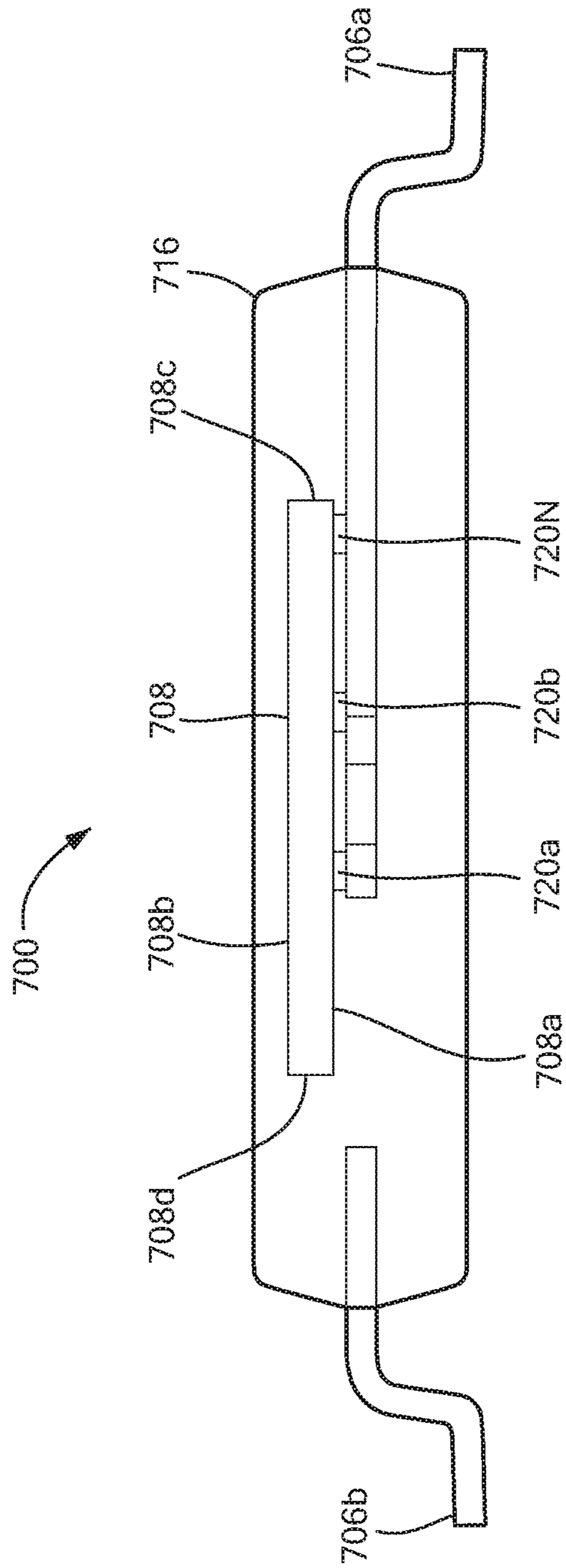


FIG. 7A

SYSTEMS AND METHODS FOR CURRENT SENSING

BACKGROUND

Some conventional electrical current sensors are positioned near a current-carrying conductor to sense a magnetic field generated by the current through the conductor. The current sensor generates an output signal having a magnitude proportional to the magnetic field induced by the current through the conductor.

The accuracy with which a magnetic field-based current sensor senses an intended current can be affected by its immunity to stray magnetic fields. Some conventional current sensors employ shields, sometimes in the form of a ferrite or other magnetic core positioned around the conductor, to concentrate the magnetic field in the vicinity of the sensor and to thereby provide a level of shielding against stray fields, such as those that may be caused by currents flowing in adjacent conductors.

SUMMARY

Systems and methods described herein are directed towards current sensing by a current sensor having two or more magnetic field sensing elements that are oriented to sense a magnetic field generated by a current through an external conductor in the same direction. Each of the two or more magnetic field sensing elements can generate a magnetic field signal indicative of a distance between the respective magnetic field sensing element and the current carrying conductor. In some embodiments, the outputs of the magnetic field sensing elements can be subtracted to differentially measure the magnetic field generated by the current through the conductor. Thus, a difference signal corresponding to the difference between the magnetic field signals can be generated that rejects stray fields and is indicative of the current through the conductor.

The current sensing can be performed by positioning the current sensor over an edge (e.g., straddling the edge) of the conductor such that at least one first magnetic field sensing element is over or otherwise vertically aligned with the conductor and at least one second magnetic field sensing element is not over or otherwise vertically aligned with the conductor. The magnetic field sensing elements may be spaced from each to measure a gradient. Thus, the spacing may be selected based on a desired gradient (e.g., largest gradient) and/or a level of the current through the conductor.

The current sensor may be provided in a package having a lead frame that allows for high isolation between the conductor and the output signal lead(s) of the sensor. For example, the current sensor can include one or more substrates (e.g., semiconductor substrates) that support the magnetic field sensing elements and the lead frame can include a die attach paddle and a plurality of leads. The one or more substrates can be attached to the die attach paddle. In an embodiment, a first plurality of leads adjacent to a first side of the die attach paddle can be coupled to the die attach paddle and a second plurality of leads adjacent to a second side of the die attach paddle can be spaced from the die attach paddle. With this arrangement, one set of leads can be coupled to a non-current carrying surface adjacent to the conductor and the second set of leads can be coupled to the current carrying conductor but spaced from the die attach paddle. With the second set of leads spaced from (i.e., not in contact with) the die attach paddle, high isolation from the conductor is achieved. The spacing between the second set

of leads and the die attach paddle may be selected based at least in part on a level of the current, a voltage of the conductor, and isolation requirements. It should be appreciated that in the current sensor arrangements described herein, the conductor can be isolated from the one or more substrates and the first plurality of leads through a variety of different techniques. For example, in some embodiments, to provide voltage isolation, the die attach paddle can be coupled to the second plurality of leads. However, an isolation layer (e.g., tape, non-conductive die attach paddle) can be disposed between the one or more substrates and the die attach paddle and one or more wire bonds can be coupled from the one or more substrates to the signal leads.

The conductor may be referred to herein as an external conductor as the current sensor is disposed over or otherwise adjacent to the conductor and the current does not flow through the current sensor package. For example, in some embodiments, the current sensor may be positioned such that it hovers over the edge of the external conductor.

A downset configuration of the die attach paddle may be provided such that at least some of the plurality of leads are positioned at different heights than the die attach paddle (and thus substrate and magnetic field sensing elements) relative to the conductor to bring the die attach paddle closer to the conductor than otherwise possible. For example, the plurality of leads can be disposed at a first height with respect to the conductor and the die attach paddle can be disposed at a second height with respect to the conductor. The first height can be greater than the second height such that the die attach paddle, substrate and plurality of magnetic field sensing elements are disposed at a lower height and in a closer proximity to the current carrying conductor, than otherwise possible.

In a first aspect, a current sensor for sensing a magnetic field generated by a current through an external conductor comprises a lead frame having a first surface and a second, opposing surface, the lead frame comprising a die attach paddle and a plurality of leads, one or more substrates attached to the die attach paddle and a plurality of magnetic field sensing elements supported by the one or more substrates. At least one first magnetic field sensing element of the plurality of magnetic field sensing elements is spaced from at least one second magnetic field sensing element of the plurality of magnetic field sensing elements and the at least one first magnetic field sensing element and the at least one second magnetic field sensing element are orientated to sense the magnetic field in the same direction. The at least one first magnetic field sensing element is configured to generate a first magnetic field signal indicative of a distance between the at least one first magnetic field sensing element and the conductor and wherein the at least one second magnetic field sensing element is configured to generate a second magnetic field signal indicative of a distance between the at least one second magnetic field sensing element and the conductor. The current sensor further comprises a circuit responsive to the first magnetic field signal and to the second magnetic field signal and configured to generate a difference signal indicative of a difference between the first magnetic field signal and the second magnetic field signal. The difference is indicative of the current carried by the conductor. For example, the first and second magnetic field signals can be proportional to the current carried by the conductor and that the proportionality constant can be indicative of the distance between the respective magnetic field sensing elements.

In some embodiments, the one or more substrates may have a first surface attached to the die attach paddle and a

second, opposing surface, and the plurality of magnetic field sensing elements can be supported by the second surface of the one or more substrates. In other embodiments, the one or more substrates may have a first surface attached to the die attach paddle and proximate to the lead frame, and a second, opposing surface distal from the lead frame and the plurality of magnetic field sensing elements can be supported by the first surface of the one or more substrates.

The at least one first magnetic field sensing element can be vertically aligned with the external conductor and the at least one second magnetic field sensing element can be positioned such that it is not vertically aligned with the external conductor. The die attach paddle may comprise one or more slits, slots or apertures. The one or more slits, slots or apertures can be configured to reduce or otherwise limit the amount of eddy currents forming in the die attach paddle.

The plurality of leads can be disposed at a first height with respect to the external conductor and the die attach paddle is disposed at a second, different height with respect to the external conductor, wherein the first height is greater than the second height.

In some embodiments, a mold material encloses the one or more substrates and a portion of the lead frame including the die attach paddle. A first plurality of the leads can extend from a first side of the mold material and a second plurality of the leads can extend from a second, opposite side of the mold material, and the die attach paddle is attached to one or more of the first plurality of the leads and is spaced from the second plurality of leads.

The plurality of magnetic field sensing elements may comprise at least one of a Hall effect element or a magnetoresistance element. The magnetoresistance element may comprise at least one of Indium Antimonide (InSb), a giant magnetoresistance (GMR) element, an anisotropic magnetoresistance (AMR) element, a tunneling magnetoresistance (TMR) element or a magnetic tunnel junction (MTJ) element.

In another aspect, a current sensor system is provided comprising a printed circuit board (PCB), a conductor supported by the PCB and configured to carry a current and a current sensor comprising a plurality of magnetic field sensing elements supported by one or more substrates. At least one of the plurality of magnetic field sensing elements is vertically aligned with the conductor and at least one of the plurality of magnetic field sensing elements is not vertically aligned with the conductor.

A plurality of slots (or slits) may be formed in the conductor in a direction of the current. The slots (or slits) may be formed to reduce or otherwise mitigate adverse effects of skin effect and current crowding at higher current frequencies. The conductor has an edge and the at least one first magnetic field sensing element and the at least one second magnetic field sensing element can be positioned such that they are substantially equidistant from the edge.

The current sensor may further comprise a circuit responsive to a first magnetic field signal from the at least one magnetic field sensing element that is vertically aligned with the conductor and to a second magnetic field signal from the at least one magnetic field sensing element that is not vertically aligned with the conductor. The circuit can be configured to generate a difference signal indicative of the difference between the first magnetic field signal and the second magnetic field signal. The difference signal can be indicative of the current carried by the conductor.

In some embodiments, the conductor comprises a conductive trace supported by the PCB and proximate to the current sensor. In other embodiments, the conductor com-

prises a conductive trace disposed distal from the current sensor such that the PCB is positioned between the conductive trace and the current sensor.

The current sensor may further comprise a lead frame having a first surface adjacent to the PCB and a second, opposing surface distal from the PCB, the lead frame comprising a die attach paddle and a plurality of leads, and the one or more substrates attached to the die attach paddle. In some embodiments, the one or more substrates can have a first surface attached to the die attach paddle and a second, opposing surface and the plurality of magnetic field sensing elements can be supported by the second surface of the one or more substrates. In other embodiments, the one or more substrates can have a first surface attached to the die attach paddle and proximate to the lead frame, and a second, opposing surface distal from the lead frame, and the plurality of magnetic field sensing elements can be supported by the first surface of the one or more substrates.

The die attach paddle may comprise one or more slits, slots or apertures. The plurality of leads can be disposed at a first height with respect to the conductor and the die attach paddle can be disposed at a second, different height with respect to the conductor. The first height can be greater than the second height.

The current sensor system may comprise a mold material enclosing the one or more substrates and a portion of the lead frame including the die attach paddle. A first plurality of the leads may extend from a first side of mold material and a second plurality of the leads may extend from a second, opposite side of the mold material. The die attach paddle can be attached to the first plurality of the leads and is not attached to the second plurality of leads.

The plurality of magnetic field sensing elements may comprise at least one of a Hall effect element or a magnetoresistance element. The magnetoresistance element may comprise at least one of Indium Antimonide (InSb), a giant magnetoresistance (GMR) element, an anisotropic magnetoresistance (AMR) element, a tunneling magnetoresistance (TMR) element or a magnetic tunnel junction (MTJ) element.

In another aspect, a current sensor for sensing a magnetic field generated by a current through an external conductor is provided comprising a lead frame having a first surface and a second, opposing surface, a die attach paddle, a first plurality of leads and a second plurality of leads, the die attach paddle having first side adjacent to the first plurality of leads and second, opposing side adjacent to the second plurality of leads, wherein the first side of the die attach paddle is attached to at least one of the first plurality of leads and wherein the second side of the die attach paddle is spaced from the second plurality of leads, one or more substrates attached to the die attach paddle and a plurality of magnetic field sensing elements supported by the one or more substrates. At least one first magnetic field sensing element of the plurality of magnetic field sensing elements is spaced from at least one second magnetic field sensing element of the plurality of magnetic field sensing elements such that the at least one first magnetic field sensing element is closer to the first side of the die attach paddle than to the second side of the die attach paddle and the at least one second magnetic field sensing element is closer to the second side of the die attach paddle than to the first side of the die attach pad.

In some embodiments, the one or more substrates can have a first surface attached to the die attach paddle and a second, opposing surface and the plurality of magnetic field sensing elements can be supported by the second surface of

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the one or more substrates. In other embodiments, the one or more substrates can have a first surface attached to the die attach paddle and proximate to the lead frame, and a second, opposing surface distal from the lead frame and the plurality of magnetic field sensing elements can be supported by the first surface of the one or more substrates.

The at least one first magnetic field sensing element can be configured to generate a first magnetic field signal indicative of a distance between the at least one first magnetic field sensing element and the conductor and the at least one second magnetic field sensing element can be configured to generate a second magnetic field signal indicative of a distance between the at least one second magnetic field sensing element and the conductor. The current sensor may further comprise a circuit responsive to the first magnetic field signal and to the second magnetic field signal and configured to generate a difference signal indicative of a difference between the first magnetic field signal and the second magnetic field signal. The difference can be indicative of the current carried by the conductor.

In some embodiments, the at least one first magnetic field sensing element is vertically aligned with the conductor and the at least one second magnetic field sensing element is not vertically aligned with the conductor. The die attach paddle may comprise one or more slits, slots or apertures.

The first and second plurality of leads can be disposed at a first height with respect to the conductor and the die attach paddle can be disposed at a second, different height with respect to the conductor. The first height can be greater than the second height.

The current sensor may further comprise a mold material enclosing the one or more substrates and a portion of the lead frame including the die attach paddle. The first plurality of the leads can extend from a first side of mold material and the second plurality of the leads can extend from a second, opposite side of the mold material.

The plurality of magnetic field sensing elements may comprise at least one of a Hall effect element or a magnetoresistance element. The magnetoresistance element may comprise at least one of Indium Antimonide (InSb), a giant magnetoresistance (GMR) element, an anisotropic magnetoresistance (AMR) element, a tunneling magnetoresistance (TMR) element or a magnetic tunnel junction (MTJ) element.

In another aspect, a method for sensing a magnetic field generated by a current through an external conductor comprises providing a lead frame having a first surface and a second, opposing surface, the lead frame comprising a die attach paddle and a plurality of leads, wherein one or more substrates are attached to the die attach paddle, providing a current sensor comprising a plurality of magnetic field sensing elements supported by a surface of one or more substrates, wherein at least one first magnetic field sensing element of the plurality of magnetic field sensing elements is spaced from at least one second magnetic field sensing element of the plurality of magnetic field sensing elements, sensing the magnetic field by the at least one first magnetic field sensing element and the at least one second magnetic field sensing element, wherein the at least one first magnetic field sensing element and the at least one second magnetic field sensing element are orientated to sense the magnetic field in the same direction, generating a first magnetic field signal indicative of a first distance between the at least one first magnetic field sensing element and the conductor, generating a second magnetic field signal indicative of a second distance between the at least one second magnetic field sensing element and the conductor and generating a

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difference signal indicative of a difference between the first magnetic field signal and the second magnetic field signal, wherein the difference is indicative of the current carried by the conductor.

The method may further comprise positioning the at least one first magnetic field sensing element such that it is vertically aligned with the conductor and positioning the at least one second magnetic field sensing element such that it is not vertically aligned with the conductor. One or more slits, slots or apertures may be formed in the die attach paddle.

In some embodiments, the method further comprises disposing the plurality of leads at a first height with respect to the conductor and disposing the die attach paddle at a second, different height with respect to the conductor. The first height can be greater than the second height.

The one or more substrates and a portion of the lead frame including the die attach paddle may be enclosed in a mold material. A first plurality of the leads may extend from a first side of mold material and a second plurality of the leads may extend from a second, opposite side of the mold material. The die attach paddle can be attached to one or more of the first plurality of the leads and is spaced from the second plurality of leads.

The plurality of magnetic field sensing elements may comprise at least one of a Hall effect element or a magnetoresistance element. The magnetoresistance element may comprise at least one of Indium Antimonide (InSb), a giant magnetoresistance (GMR) element, an anisotropic magnetoresistance (AMR) element, a tunneling magnetoresistance (TMR) element or a magnetic tunnel junction (MTJ) element.

In another aspect, a method for sensing a magnetic field generated by a current through a conductor is provided comprising providing a printed circuit board (PCB) supporting the conductor, providing a current sensor comprising a plurality of magnetic field sensing elements supported by one or more substrates, positioning the current sensor over an edge of the conductor such that a first magnetic field sensing element of the plurality of magnetic field sensing elements is vertically aligned with the conductor and a second magnetic field sensing element of the plurality of magnetic field sensing elements is not vertically aligned with the conductor; wherein the conductor is supported by the PCB and configured to carry the current, and computing a difference between a first magnetic field signal generated by the first magnetic field sensing element and a second magnetic field signal generated by the second magnetic field sensing element, wherein the difference is indicative of the current through the conductor.

The method may further comprise forming a plurality of slots formed in the conductor in a direction of the current. In some embodiments, positioning the current sensor over the edge of the conductor comprises positioning the at least one first magnetic field sensing element and the at least one second magnetic field sensing element such that they are substantially equidistant from the edge.

The method may further comprise providing the conductor as a conductive trace disposed distal from the current sensor such that the PCB is positioned between the conductive trace and the current sensor.

In some embodiments, providing the current sensor further comprises providing a lead frame having a first surface adjacent to the PCB and a second, opposing surface distal from the PCB, the lead frame comprising a die attach paddle and a plurality of leads. A first surface of the one or more substrates can be coupled to the die attach paddle, wherein

the plurality of magnetic field sensing elements can be supported by a second, opposite surface of the one or more substrates. In other embodiments, a first surface of the one or more substrates can be coupled to the die attach paddle, wherein the plurality of magnetic field sensing elements can be supported by the first surface of the one or more substrates.

One or more slits, slots or apertures in the die attach paddle. The method may further comprise providing the plurality of leads at a first height with respect to the conductor and providing the die attach paddle at a second, different height with respect to the conductor. The first height can be greater than the second height.

The method may further comprise enclosing the one or more substrates and a portion of the lead frame including the die attach paddle in a mold material. A first plurality of the leads may extend from a first side of mold material and a second plurality of the leads may extend from a second, opposite side of the mold material. The die attach paddle can be attached to one or more of the first plurality of the leads and is not attached to the second plurality of leads.

The plurality of magnetic field sensing elements may comprise at least one of a Hall effect element or a magnetoresistance element. The magnetoresistance element may comprise at least one of Indium Antimonide (InSb), a giant magnetoresistance (GMR) element, an anisotropic magnetoresistance (AMR) element, a tunneling magnetoresistance (TMR) element or a magnetic tunnel junction (MTJ) element.

In another aspect, a current sensor for sensing a magnetic field generated by a current through an external conductor, the magnetic field having direction associated with a direction of the current through the conductor, comprises a first means for sensing the magnetic field generated by the current to generate a first magnetic field signal indicative of a distance between the first magnetic field sensing means and the conductor, a second means for sensing the magnetic field generated by the current to generate a second magnetic field signal indicative of a distance between the second magnetic field sensing means and the conductor, means for supporting the first magnetic field sensing means and the second magnetic field sensing means in a spaced relationship, but with both the first and second magnetic field sensing means oriented to sense the magnetic field in the same direction and means for determining a difference between the first magnetic field signal and the second magnetic field signal, wherein the difference is indicative of the current through the conductor.

The first magnetic field sensing means can be vertically aligned with the external conductor and the second magnetic field sensing means can be positioned such that it is not vertically aligned with the external conductor.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing features may be more fully understood from the following description of the drawings in which:

FIG. 1 shows a current sensor having a plurality of magnetic field sensing elements supported by a substrate and attached to a die attach paddle;

FIG. 1A shows an exploded view of the current sensor of FIG. 1;

FIG. 2 shows the current sensor of FIG. 1 positioned over an edge of a conductor;

FIG. 2A shows the spacing of one or more magnetic field sensing elements within the current sensor of FIG. 1 relative to the conductor;

FIG. 2B shows one or more slits formed in a conductor;

FIGS. 2C-2F show different embodiments of conductors comprising one or more conductive traces and a printed circuit board relative to the current sensor of FIG. 1;

FIG. 3 is a plain view of the current sensor of FIG. 1;

FIG. 4 is a circuit diagram of a current sensor;

FIG. 5 is a flow diagram of a method for sensing a magnetic field generated by a current through a conductor by the current sensor of FIG. 1;

FIG. 6 is a flow diagram of a method for sensing a magnetic field generated by a current through a conductor by the current sensor of FIG. 1.

FIG. 7 shows a flip chip current sensor; and

FIG. 7A shows a side view of the flip chip current sensor of FIG. 7.

DETAILED DESCRIPTION

Before describing the present invention, some introductory concepts and terminology are explained.

As used herein, the term “magnetic field sensing element” is used to describe a variety of electronic elements that can sense a magnetic field. The magnetic field sensing element can be, but is not limited to, a Hall-effect element, a magnetoresistance element, or a magnetotransistor. As is known, there are different types of Hall-effect elements, for example, a planar Hall element, a vertical Hall element, and a Circular Vertical Hall (CVH) element. As is also known, there are different types of magnetoresistance elements, for example, a semiconductor magnetoresistance element such as an Indium Antimonide (InSb) element, a giant magnetoresistance (GMR) element, for example, a spin valve, an anisotropic magnetoresistance element (AMR), a tunneling magnetoresistance (TMR) element, and a magnetic tunnel junction (MTJ). The magnetic field sensing element may be a single element or, alternatively, may include two or more magnetic field sensing elements arranged in various configurations, e.g., a half bridge or full (Wheatstone) bridge. Depending on the device type and other application requirements, the magnetic field sensing element may be a device made of a type IV semiconductor material such as Silicon (Si) or Germanium (Ge), or a type III-V semiconductor material like Gallium-Arsenide (GaAs) or an Indium compound, e.g., Indium-Antimonide (InSb).

As is known, some of the above-described magnetic field sensing elements tend to have an axis of maximum sensitivity parallel to a substrate that supports the magnetic field sensing element, and others of the above-described magnetic field sensing elements tend to have an axis of maximum sensitivity perpendicular to a substrate that supports the magnetic field sensing element. In particular, planar Hall elements tend to have axes of sensitivity perpendicular to a substrate, while metal based or metallic magnetoresistance elements (e.g., GMR, TMR, AMR) and vertical Hall elements tend to have axes of sensitivity parallel to a substrate.

As used herein, the term “magnetic field sensing circuit” is used to describe a circuit that uses a magnetic field sensing element, generally in combination with other circuits. Magnetic field sensing circuits are used in a variety of applications, including, but not limited to, an angle sensor that senses an angle of a direction of a magnetic field, a current sensor that senses a magnetic field generated by a current carried by a current-carrying conductor, a magnetic switch that senses the proximity of a ferromagnetic object, a rotation detector that senses passing ferromagnetic articles, for example, magnetic domains of a ring magnet or a ferromagnetic target (e.g., gear teeth) where the magnetic

field sensor is used in combination with a back-biased or other magnet, and a magnetic field sensor that senses a magnetic field density of a magnetic field.

Now referring to FIG. 1, a current sensor **100** includes a lead frame **102**, a substrate **108** and a plurality of magnetic field sensing elements **110a-110n** supported by substrate **108**. Current sensor **100** can be positioned over an edge of an external conductor (FIG. 2) and be configured to perform current sensing based at least in part on a relative spacing between each of the at least two of the magnetic field sensing elements **110a-110n** and the conductor.

Magnetic field sensing elements **110a-110n** are oriented or otherwise positioned such that each of the magnetic field sensing elements **110a-110n** can sense a magnetic field generated by a current through an external conductor (FIG. 2) in the same direction. However, each of the magnetic field sensing elements **110a-110n** can be positioned at different distances from the external conductor and thus generate magnetic field signals at different levels based at least in part on their respective distance from the external conductor. A difference between the magnetic field signals generated by each of the magnetic field sensing elements **110a-110n** can be used to determine the current through the external conductor. Further, the spacing between at least one first magnetic sensing element **110a** and at least one second magnetic field sensing element **110n** may be selected to optimize the gradient between the magnetic fields experienced by each of the sensing elements **110a, 110n**.

Lead frame **102** includes a die attach paddle **104** and a plurality of leads **106**. Substrate (e.g., semiconductor substrate) or die **108** is attached to die attach paddle **104**, as may be achieved with an adhesive layer **107**. For example, and as illustrated in FIG. 1, a second surface **108b** of substrate **108** is coupled to a first surface **104a** of die attach paddle **104** (i.e., die-up configuration). It should be appreciated however, that in other embodiments, a first surface **108a** of substrate **108** may be coupled to a second surface **104b** of die attach paddle **104** (i.e., flip chip configuration as shown in FIG. 7). It will also be understood that while a single semiconductor die **108** is shown, the current sensor can include more than one die, with each such die supporting magnetic field sensing element(s) and/or supporting circuitry.

Lead frame **102** can be configured to provide high voltage isolation between signal leads as may carry relatively low voltage signals and high voltage leads as may contact an external conductor. For example, leads **106** includes a first plurality of leads **106a** extending from a first side **104c** of die attach paddle **104** and a second plurality of leads **106b** spaced from (e.g., not in contact with) a second side **104d** of die attach paddle **104**. Leads **106a** may be coupled to a non-current carrying surface and leads **106b** may be coupled to a current carrying surface of a conductor. For example, in some embodiments, leads **106a** may be coupled to a microcontroller or other surface that may utilize low voltage current measurement signals. It should be appreciated that a non-current carrying surface as referred to herein may refer to a low voltage surface or a surface carry a current less than a current carrying surface of a conductor (e.g., conductor **206** of FIG. 2.). Thus, leads **106b** (coupled to current carrying conductor) may be electrically isolated from die attach paddle **104**. The space gap between leads **106b** and die attach paddle **104** is shown further below in connection with FIG. 3.

It should be appreciated that in the current sensor arrangements described herein, the conductor (e.g., conductor **206** of FIG. 2.) can be isolated from the one or more substrates

108 and first plurality of leads **106a** through a variety of different techniques. For example, in some embodiments, to provide voltage isolation, die attach paddle **104** can be coupled to second plurality of leads **106b**. However, an isolation layer (e.g., tape, non-conductive die attach paddle) can be disposed between the one or more substrates **108** and die attach paddle **104** and one or more wire bonds can be coupled from the one or more substrates **108** to the signal leads.

Die attach paddle **104** may include one or more cutouts, slits, slots or apertures **114a, 114b** to reduce eddy currents. For example, eddy currents may be formed near a current carrying conductor and oppose magnetic fields, generated by the current carrying conductor that are to be sensed by magnetic field sensing elements **110a-110n**. The one or more cutouts **114a, 114b** may be configured to limit the amount of eddy currents forming in the die attach paddle **104**. The one or more cutouts **114a, 114b** will be described in greater detail below with respect to FIG. 3.

Substrate **108** may include a semiconductor substrate. In some embodiments, substrate **108** may include a semiconductor material and any material used for supporting semiconductor materials. For example, substrate **108** may include, but not limited to, a semiconductor material disposed on at least one of glass, ceramic, or polymer.

A mold material **116** is provided to enclose die attach paddle **104**, substrate **108**, magnetic field sensing elements **110a-110n** and portions of leads **106**, as shown.

Magnetic field sensing elements **110a-110n** may include one or more Hall effect elements or one or more magnetoresistance elements. For example, the magnetoresistance elements may include at least one of Indium Antimonide (InSb), a giant magnetoresistance (GMR) element, an anisotropic magnetoresistance (AMR) element, a tunneling magnetoresistance (TMR) element or a magnetic tunnel junction (MTJ) element.

In an embodiment, current sensor lead frame can have a downset configuration such that portions of the plurality of leads **106** are positioned at different heights than the die attach paddle **104** (and thus, also than the substrate **108** and magnetic field sensing elements **110a-110n**).

For example, and referring also to the exploded view of current sensor **150** in FIG. 1A, leads **106a** include a first portion **140a** at a first height and a connect portion **142** coupled between the first portion **140a** and the die attach paddle **104**. Thus, the first lead portions **140a** can be at a first height and the die attach paddle **104** can be at a different height that in some embodiments is less than the first height. In such embodiments, when the current sensor is positioned relative to a current carrying conductor, the first lead portions **140a** may be higher than the die attach paddle **104** relative to the conductor, in order to thereby bring the die attach paddle closer to the conductor than otherwise possible.

A second portion **140b** of leads **106a** may be at a second lower height than portions **140a** to provide surface mount pads for coupling to a printed circuit board or other support structure. Similarly leads **106b** can have a first portion **144a** at a first height and second portions **144b** at a second, lower height to form surface mount pads.

The first portion **144a** of leads **106b** can be spaced from (i.e., not in contact with) die attach paddle **104**. Thus, in applications in which leads **106b** are coupled to a current carrying conductor (see, e.g., FIG. 2), die attach paddle **104** and electrically coupled leads **106a** can be electrically isolated from the current carrying conductor.

Now referring to FIG. 2, a current sensor 200 is positioned over an edge 212 of external conductor 206 that is configured to carry a current 210. Current sensor 200 may be the same as or substantially similar to current sensor 100 of FIG. 1 and thus may include a plurality of magnetic field sensing elements configured to sense a magnetic field generated by the current 210 through conductor 206. In an embodiment, the plurality of magnetic field sensing elements can be oriented or otherwise positioned within current sensor 200 to sense the magnetic field generated by current 210 through conductor 206 in the same direction. In other words, the magnetic field sensing elements are positioned within the sensor package 200 such that when the sensor 200 is disposed in proximity to (i.e., disposed over) the conductor 206, the magnetic field (generated by the current through the conductor) incident on each of the sensing elements has the same polarity.

As illustrated in FIG. 2, a first plurality of leads 204a of current sensor 200 are coupled to a non-current carrying surface 208 and a second plurality of leads 204b are coupled to conductor 206. Thus, current sensor 200 can be positioned over edge 212 of conductor 206, as shown. First plurality of leads 204a and second plurality of leads 204b may be the same as or substantially similar to respective leads 106a and leads 106b of current sensor 100 of FIG. 1. Thus, in an embodiment, leads 204a may be coupled to a die attach paddle within current sensor 200 and leads 204b may be spaced from (e.g., not in contact with) the die attach paddle within current sensor 200. Thus, current sensor 200 may provide high voltage isolation between leads 204a and conductor 206.

Referring also to FIG. 2A, current sensor 200 can be positioned over edge 212 of conductor 206 such that a first magnetic sensing element 260 is vertically aligned with (here over) conductor 206 and a second magnetic sensing element 262 is not vertically aligned with conductor 206 and instead is aligned with a non-current carrying surface 208 (i.e., with magnetic field sensing elements 260, 262 straddling the edge 212 of the conductor). Current sensor 200 can be configured to perform current sensing by comparing (e.g., subtracting) outputs of first and second magnetic field sensing elements 260, 262 in order to thereby sense the current by sensing a gradient between the magnetic field sensed by each sensing element 260, 262. Thus, the sensing methodology requires a difference (or gradient) in the magnetic fields experienced by the sensing elements 260, 262.

The position of current sensor 200 relative to conductor 206 can be selected based at least in part on a level of the current through conductor 206 and thus, the expected magnetic field strength, the sensitivity of the magnetic field sensing elements, and/or a magnetic field gradient to be measured. In some embodiments, it may be desirable to position the sensor 200 so that the sensing elements 260, 262 experience the largest magnetic field gradient possible (i.e., the largest difference between the magnetic fields experienced by the spaced magnetic field sensing elements 260, 262) as may occur when at least one first magnetic sensing element 260 is vertically aligned with the current carrying conductor 206 and at least one second magnetic sensing element 262 is not vertically aligned with the current carrying conductor 206. To this end, a first portion 200a of current sensor 200 is vertically aligned with (here over) conductor 206 and a second portion 200b is not vertically aligned with conductor 206 and instead is vertically aligned with a non-current carrying surface 208. In one such configuration, current sensor 200 may be positioned such that an edge 200c of first portion 200a and an edge 200d of second

portion 200b are equidistant from edge 212 of conductor 206, here represented by a distance “d1” (and more specifically such that the sensing elements 260, 262 are equidistant from the conductor edge 212, here represented by a distance “d2”). Thus, first portion 200a and second portion 200b can be equal in size (e.g., width, length).

In other embodiments, first portion 200a and second portion 200b may be different in size. For example, current sensor 200 may be positioned such a distance from edge 212 of conductor 206 to edge 200c of first portion 200a is greater than a distance from edge 212 of conductor 206 to edge 200d of second portion 200b. In other embodiments, current sensor 200 may be positioned such a distance from edge 212 of conductor 206 to edge 200c of first portion 200a is less than a distance from edge 212 of conductor 206 to edge 200d of second portion 200b. In such configurations, the magnetic field sensing elements 260, 262 may not be equidistantly spaced from the conductor edge 212.

In some embodiments, all of current sensor 200 (or at least both magnetic field sensing elements 260, 262) may be vertically aligned (i.e., positioned over) conductor 206. In such embodiments, the sensing elements 260, 262 are not centered with respect to the conductor in order to ensure a gradient in the magnetic fields experienced by the sensing elements. In other embodiments, current sensor 200 can be positioned relative to conductor 206 such no portion (or at least neither magnetic field sensing element) is vertically aligned (i.e., positioned over) conductor 206 and instead current sensor 200 is vertically offset with respect to conductor 206.

It should be appreciated that although current sensor 200 is shown to include two magnetic field sensing elements 260, 262 in FIG. 2A, in other embodiments, current sensor 200 (or any current sensor described herein) may include more than two magnetic field sensing elements.

Now referring to FIG. 2B, conductor 282 is provided having one or more slits 284a-284n (here four). Conductor 282 may be the same as or substantially similar to conductor 206 of FIGS. 2-2A, however, conductor 282 includes slits 284a-284n. Slits 284a-284n may be formed to reduce or otherwise mitigate adverse effects of skin effect and current crowding at higher current frequencies. For example, as current flows through conductor 282 at high frequency, the current tends to crowd or migrate towards the outer surfaces and edges of conductor 282. Conductor slits 284a-284n have the effect of making the conductor 282 present electrical characteristics as if the current were being carried by multiple parallel wires, the number of wires being based on the number of slits 284a-284n in order to thereby normalize or otherwise equalize the current sensor response over frequency.

The slits 284a-284n may be formed such that their length is substantially parallel to a direction of the current flow through the conductor. In some embodiments, multiple slits 284a-284n may be formed such that they are equidistant from each other. In other embodiments, multiple slits 284a-284n may be formed such that they have different distances between them. The total number of slits 284a-284n may vary based at least in part on properties of conductor 282 and/or a particular application of a current sensor. For example, in some embodiments, conductor 282 may have one slit 284a-284n. In other embodiments, conductor 282 may have two or more slits 284a-284n.

Now referring to FIGS. 2C-2F, conductor 206 may take the form of a conductive trace 220 and a printed circuit board (PCB) 224. It should be appreciated that in some embodiments, each of the current traces illustrated in FIGS.

2C-2F may include one or more slits, such as slits **284a-284n** described above with respect to FIG. 2B. Conductive trace **220** may be formed, disposed on or otherwise supported by one or more surfaces of the PCB **224**. For example, and as illustrated in FIG. 2C (in which the current can be considered to flow into the page), conductive trace **220** may be supported by a first surface **224a** of PCB **224** such that conductive trace is disposed proximal to current sensor **200**.

In FIG. 2D, a first conductive trace **220a** is supported by first surface **224a** of PCB **224** and a second conductive trace **220b** is supported by a second opposite surface **224b** of PCB **224**. Current can be considered to flow into the page through both the first and second conductive traces **220a, 220b**. This configuration can allow for higher current flow than otherwise possible, while also maintaining thermal performance.

In FIG. 2E, first conductive trace **220a** is supported by first surface **224a** of PCB **224** and second conductive trace **220b** is supported by second opposite surface **224b** of PCB **224** and one or more additional conductive trace layers **220c** are embedded within PCB **224**. Current can be considered to flow into the page through both the conductive traces **220a, 220b, and 220c**. This configuration can allow for maximum current flow, while also maintaining thermal performance. In embodiments in which the conductor is comprised of more than one conductive trace (e.g., FIGS. 2D and 2E), it will be appreciated that the multiple conductive traces can be electrically coupled in parallel so that current to be sensed by current sensor **200** flows in parallel through the multiple conductive traces. In some embodiments, the multiple conductive traces can be electrically coupled in series so that current to be sensed by current sensor **200** flows in series through the multiple conductive traces to increase the current to be sensed by current sensor **200** and improve sensor resolution.

In other embodiments and as illustrated in FIG. 2F, conductive trace **220** may be supported by second surface **224b** of PCB **224** such that conductive trace **220** is disposed distal from current sensor **200** and PCB **224** is disposed between conductive trace **220** and current sensor **200**. Here again, current can be considered to flow into the page. This configuration provides a very high level of voltage isolation. It should be appreciated, that in the embodiment of FIG. 2F, current sensor **200** is coupled to a first surface **224a** of PCB **224** and conductive trace **220** is supported by the second surface **224b** to provide the voltage isolation. Thus, in some embodiments, secondary leads extending from current sensor **200** can be coupled to current sensor **200** and not isolated or otherwise spaced apart from current sensor **200** (in contrast to current sensor **100** described above with respect to FIG. 1).

Now referring to FIG. 3, a current sensor **300** is provided having a lead frame **302**, the lead frame comprising a die attach paddle **304**, a first plurality of leads **306a** and a second plurality of leads **306b**. A substrate **308** is coupled to die attach paddle **304**. A first surface **308a** of substrate **308** supports a first magnetic field sensing element **310a** and a second magnetic field sensing element **310b**.

Die attach paddle **304** may include one or more cutouts **314a, 314b** (or slits, slots, apertures or other features) to limit or otherwise reduce the amount of eddy currents forming in die attach paddle **304** which may affect magnetic field sensing elements **310a, 310b**. For example, eddy currents may be formed near a current carrying conductor and oppose magnetic fields generated by the current carrying conductor that are to be sensed by magnetic field sensing

elements **310a, 310b**. Thus, one or more cutouts **314a, 314b** (here two) may be formed in die attach paddle **304** to reduce eddy currents.

As illustrated in FIG. 3, a first cutout **314a** and a second cutout **314b** may be formed such that each is aligned with (here under) at least one of magnetic field sensing elements **310a, 310b** respectively. In other embodiments, cutouts **314a, 314b** may be formed such that one or both are not generally aligned (e.g., not centered) with respect to at least one of magnetic field sensing elements **310a, 310b**.

Second plurality of leads **306b** are spaced a distance "x" from die attach paddle **304** and thus not in contact with die attach paddle. The spacing "x" may be selected to isolate die attach paddle **304** from a current carrying conductor to which the second plurality of leads **306b** may be coupled. In some embodiments, the spacing "x" may be selected based at least in part on a level of the current through or voltage at the conductor and/or isolation requirements.

Now referring to FIG. 4, a current sensor system **400** includes a current sensor **404** and conductor **402**. Current sensor **404** may be the same as, or substantially similar to current sensor **100** of FIG. 1. Current sensor **404** includes at least two spaced magnetic field sensing elements **405** and a controller circuit **436**. Controller circuit **436** can generate various control signals to control processing the output signals of magnetic field sensing elements **405** in order to thereby provide a current sensor output signal **428** indicative of a level of current through conductor **402**. It should be appreciated that the output signals of the magnetic field sensing elements can be proportional to the current carried by conductor **402** and that the proportionality constant can be indicative of the distance between the respective magnetic field sensing elements of current sensor **404**.

An input/output circuit (I/O) **438** coupled to controller **436** can control communication between current sensor **404** and various external devices or systems, such as an Engine Control Unit (ECU) in automotive applications of the current sensor system **400**. For example, in some embodiments, I/O circuit **438** may include a clock (SCL) pin to receive a clock signal and a data (SDA) pin to receive and/or send a data signal. The current sensor system **400** may include a power module **440** to power circuitry within the sensor. For example, the power module **440** may include a regulator configured to receive power from a battery.

Current sensor **404** is positioned proximate to conductor **402** to sense a magnetic field generated by a current through conductor **402**. To this end, current sensor **404** includes magnetic field sensing elements **405** responsive to receive a driver signal **407** from a bridge driver **406**. In the example, current sensor **404** of FIG. 4, magnetic field sensing elements **405** include four magnetoresistance elements coupled in a bridge configuration, such as a Wheatstone bridge. For example, magnetoresistance elements **405** may be coupled such that each leg of the bridge includes two magnetoresistance elements positioned adjacent to one another, with one such leg spaced from the other leg. For example, magnetoresistance elements **405** may be coupled such that each leg of the bridge includes two magnetoresistance elements positioned diagonal from each other to form each respective leg of the bridge or group of elements (e.g., element in left leg upper position and element in right leg lower position form a first bridge leg and element in left leg lower position and element in right leg upper position form a second bridge).

With this arrangement, a differential output signal of the bridge (taken between intermediate nodes of each bridge leg) may result in a differential signal that rejects stray fields from sources other than the current through the conductor

402. For example, one bridge leg can provide sensing element **260** (FIG. 2A) and the other bridge leg can provide sensing element **262** (FIG. 2A) so that the resulting differential signal is indicative of the difference between the magnetic field sensed by each bridge leg. The magnetoresistance elements **405** may include at least one of at least one of an Indium Antimonide (InSb) element, a giant magnetoresistance (GMR) element, an anisotropic magnetoresistance (AMR) element, a tunneling magnetoresistance (TMR) element or a magnetic tunnel junction (MTJ) element. It should be appreciated that, in some embodiments, magnetic field sensing elements **405** may be provided as one or more Hall effect elements.

Controller circuit **436** can include or be coupled to a bridge trim circuit **408** configured to improve the accuracy of the current sensor output signal **428** by trimming the sensing elements of the bridge **405**. For example, in the presence of a reference magnetic field (as may be applied during production), bridge trim circuit **408** can provide a trim signal **409** to magnetic field sensing elements **405** to trim the elements of the bridge **504** in order to thereby ensure that the sensitivity of the individual elements and/or legs of the bridge is matched.

Magnetic field sensing elements **405** can generate a differential magnetic field signal for coupling to a first differential amplifier **410**. One or more outputs of first amplifier **410** are coupled to one or more inputs of an H bridge circuit **412**. H bridge circuit **412** can include multiple field effect transistors coupled together to compare two input signals and remove or reduce noise and/or interference (e.g., DC offset) and in some embodiments, apply a gain to the difference between the two input signals.

A compensation coil **414** can be positioned proximate to magnetic field sensing elements **405** in order to apply an equal and opposite field to the sensing elements **405** drive the differential field on the bridge to zero Gauss. The current through coil **414** necessary to bring the differential field on the sensing elements **405** to zero is sensed by a resistor **416** in order to thereby implement a closed loop current sensing system. It should be appreciated that although current sensor **404** is shown to be a closed loop sensor in FIG. 4, in some embodiments, current sensor **404** can be an open loop sensor.

A voltage on the sense resistor **416** is coupled to further amplifiers **418** and **420** to implement offset and gain adjustment, including temperature compensation. An output terminal **428** of current sensor **404** (e.g., VOUT) can be provided at the output of amplifier **420** to provide a signal having a level indicative of the current through the conductor **402**.

A differential comparator **422** can be provided to implement a fault detection feature. To this end, a logic gate **424** has a first input coupled to the output of comparator **422** and a second input coupled to an interrupt signal **425**. In some embodiments, logic gate **424** may include an OR gate. An output of logic gate **424** is coupled to a control input of a transistor **426** such that detection of a current greater than a predetermined level causes a fault signal **430** to be provided. Current sensor **404** can include an analog-to-digital converter (ADC) **434** can be configured to monitor analog signals within current sensor **404** (e.g., analog references).

Now referring to FIG. 5, a method **500** for sensing a magnetic field generated by a current through an external conductor begins at block **502**, by providing a current sensor comprising a plurality of magnetic field sensing elements supported by a first surface of a substrate. At least one first magnetic field sensing element (hereinafter first magnetic

field sensing element) can be spaced from at least one second magnetic field sensing element (hereinafter second magnetic field sensing element). It should be appreciated that the following description describes a current sensor having two magnetic field sensing elements, however a current sensor as described herein may include more than two magnetic field sensing elements.

The current sensor can include a lead frame having a die attach paddle and a plurality of leads. The substrate can be coupled to the die attach paddle. The plurality of leads can include a first plurality of leads coupled to the die attach paddle and a second plurality of leads spaced from the die attach paddle. For example, the first plurality of leads can be coupled to and extend from a first side of the die attach paddle and the second plurality of leads can be spaced from a second side of the die attach paddle.

The current sensor can be positioned proximate to a current carrying external conductor (e.g., external to the current sensor) to sense a magnetic field generated by the current through the conductor. The first plurality of leads may be coupled to a non-current carrying surface and the second plurality of leads may be coupled to the current carrying conductor. The second plurality of leads are spaced from the die attach paddle, thus, the die attach paddle may be isolated from the current carrying conductor.

One or more cutouts may be formed in the die attach paddle. The one or more cutouts can be formed such that they are aligned with at least one magnetic field sensing element. For example, in one embodiment, the one or more slots may be formed such that each of them are under at least one magnetic field sensing element.

In some embodiments, one or more slits may be formed in the conductor. Slits in the conductor may be aligned substantially with a direction of the current flow. For example, in some embodiments, the slits can be formed such that they are generally parallel with a direction of the current. In some embodiments having multiple slits, the slits may be formed such that they are spaced equidistant from each other. In other embodiments having multiple slits, the slits may be formed such that they are spaced at varying distances from a first slit to a next adjacent slit.

The current sensor may be formed having a downset configuration. For example, the plurality of leads can be positioned at a first height with respect to the conductor and the die attach paddle can be positioned at a second height with respect to the conductor. The first height can be greater than the second height such that the die attach paddle, substrate and plurality of magnetic field sensing elements are disposed at a lower height and in a closer proximity to the current carrying conductor than otherwise possible.

In some embodiments, a mold material may enclose the die attach paddle, a portion of the plurality of leads, and the substrate to form a current sensor package. The first plurality of the leads can extend from a first side of mold material and the second plurality of the leads can extend from a second, opposite side of the mold material.

At block **504**, the current through the external conductor can be sensed by the first magnetic field sensing element and the second magnetic field sensing element. The current sensor can be positioned such that the first magnetic field sensing element is vertically aligned with the current carrying conductor and the second magnetic field sensing element is not vertically aligned with the conductor and instead is positioned over a non-current carrying surface. However, both the first magnetic field sensing element and the second magnetic field sensing element can be oriented such that they sense the current in the same direction.

At block **506**, a first magnetic field signal indicative of a first distance between the first magnetic field sensing element and the conductor is generated. The first magnetic field sensing element can be configured to generate the first magnetic field signal based at least in part on a distance between the first magnetic field sensing element and the conductor.

At block **508**, a second magnetic field signal indicative of a second distance between the second magnetic field sensing element and the conductor. The second magnetic field sensing element can be configured to generate the second magnetic field signal based at least in part on a distance between the second magnetic field sensing element and the conductor. In an embodiment, the first and second magnetic field signals can be proportional to the current carried by the conductor and that the proportionality constant can be indicative of the distance between the respective magnetic field sensing elements.

The first and second magnetic field sensing elements are positioned at different distances from the conductor and thus the first magnetic field signal and the second magnetic field signal can be generated at different levels based on a difference in their respective distance from the conductor. For example, and as discussed above, the first magnetic field sensing element can be positioned over the conductor and the second magnetic field sensing element can be positioned such that it is not over the conductor, thus the first magnetic field signal may be at a first level and the second magnetic field signal may be at a second, different level.

At block **510**, a difference signal can be generated indicative of a difference between the first magnetic field signal and the second magnetic field signal. In an embodiment, the difference signal can be indicative of the current carried by the conductor.

Now referring to FIG. **6**, a method **600** for sensing a magnetic field generated by a current through a conductor begins at block **602** by providing a current sensor comprising a plurality of magnetic field sensing elements. A first magnetic field sensing element can be spaced from a second magnetic field sensing element within the current sensor.

The current sensor includes a lead frame having a die attach paddle and a plurality of leads. The substrate can be coupled to the die attach paddle. The plurality of leads can include a first plurality of leads coupled to the die attach paddle and a second plurality of leads spaced from the die attach paddle. For example, the first plurality of leads can be coupled to and extend from a first side of the die attach paddle and the second plurality of leads can be spaced from a second side of the die attach paddle.

At block **604**, the current sensor can be positioned over an edge of the conductor such that at least one first magnetic field sensing element is vertically aligned with the conductor and at least one second magnetic field sensing element is not vertically aligned with the conductor. With this configuration, the first and second magnetic field elements will experience a different magnetic field strength as a result of the field generated by the current through the conductor and the difference between these sensed magnetic fields can be used to detect the current level.

At block **606**, a difference between a first magnetic field signal generated by the at least one first magnetic field sensing element and a second magnetic field signal generated by the at least one second magnetic field sensing element can be computed. The difference can be indicative of the current carried by the conductor.

Now referring to FIGS. **7-7A**, a current sensor **700** includes a lead frame **702**, a substrate **708** and a plurality of

magnetic field sensing elements **710a-710n** supported by substrate **708**. Lead frame **702** includes a first plurality of leads **706a** and a second plurality of leads **706b**. Substrate **708** includes a first surface **708a** positioned proximate to leads **706a, 706b** and a second surface **708b** positioned distal from leads **706a, 706b**. In the illustrative embodiment of FIG. **7**, current sensor **700** is provided having a flip chip arrangement. For example, plurality of magnetic field sensing elements **710a-710n** are supported by the first surface **708a** of substrate **708** and thus proximate to leads **706a, 706b**.

In an embodiment, current sensor **700** can be positioned over an edge of an external conductor (FIG. **2**) and be configured to perform current sensing based at least in part on a relative spacing between each of the at least two of the magnetic field sensing elements **710a-710n** and the conductor. Lead frame **702** can be configured to provide high voltage isolation between signal leads as may carry relatively low voltage signals and high voltage leads as may contact an external conductor. For example, first plurality of leads **706a** can extend from a first side **708c** of substrate **708** and second plurality of leads **706b** can be spaced from (e.g., not in contact with) a second side **708d** of substrate **708**. Leads **706a** may be coupled to a non-current carrying surface and leads **706b** may be coupled to a current carrying surface of a conductor.

For example, in some embodiments, leads **706a** may be coupled to a microcontroller or other surface that may utilize low voltage current measurement signals. It should be appreciated that a non-current carrying surface as referred to herein may refer to a low voltage surface or a surface carry a current less than a current carrying surface of a conductor (e.g., conductor **206** of FIG. **2**). Thus, leads **706b** (coupled to current carrying conductor) may be electrically isolated from substrate **708**.

As illustrated in FIG. **7A**, a plurality of solder bumps **720a, 720b** may be disposed between substrate **708** and first plurality of leads **706a**. Second plurality of leads **706b** are spaced from second side **708d** of substrate **708**. In an embodiment, one or more solder bumps **720a-720n** may be disposed on one or more of first plurality of leads **706a** to couple substrate **708** to first plurality of leads **706a**. It should be appreciated that, in some embodiments, current sensor **700** having a flip chip configuration may include a die attach (not shown).

A mold material **716** may enclose the substrate **708** and a portion of first and second plurality of leads **706a, 706b** to form a current sensor package. First plurality of the leads **706a** can extend from a first side of mold material **716** and second plurality of the leads **706b** can extend from a second, opposite side of the mold material **716**.

Having described preferred embodiments, which serve to illustrate various concepts, structures and techniques, which are the subject of this patent, it will now become apparent that other embodiments incorporating these concepts, structures and techniques may be used. Accordingly, it is submitted that the scope of the patent should not be limited to the described embodiments but rather should be limited only by the spirit and scope of the following claims.

What is claimed:

1. A current sensor for sensing a magnetic field generated by a current through an external conductor comprising:
 - a lead frame having a first surface and a second, opposing surface, the lead frame comprising a plurality of leads;
 - one or more substrates attached to the lead frame;
 - a plurality of magnetic field sensing elements supported by the one or more substrates, wherein at least one first

magnetic field sensing element of the plurality of magnetic field sensing elements is spaced from at least one second magnetic field sensing element of the plurality of magnetic field sensing elements, wherein the at least one first magnetic field sensing element and the at least one second magnetic field sensing element are orientated to sense the magnetic field in the same direction, wherein the at least one first magnetic field sensing element is configured to generate a first magnetic field signal indicative of a first distance between the at least one first magnetic field sensing element and an edge of the conductor and wherein the at least one second magnetic field sensing element is configured to generate a second magnetic field signal indicative of a second distance between the at least one second magnetic field sensing element and the edge of the conductor, wherein the first distance and the second distance are different distances; and

a circuit responsive to the first magnetic field signal and to the second magnetic field signal and configured to generate a difference signal indicative of a difference between the first magnetic field signal and the second magnetic field signal, wherein the difference is indicative of the current carried by the conductor.

2. The current sensor of claim 1, wherein the lead frame further comprises a die attach paddle and the one or more substrates are attached to the die attach paddle.

3. The current sensor of claim 2, wherein the one or more substrates have a first surface attached to the die attach paddle and a second, opposing surface, and wherein the plurality of magnetic field sensing elements are supported by the second surface of the one or more substrates.

4. The current sensor of claim 1, wherein the one or more substrates have a first surface attached to one or more of the plurality of leads, and a second, opposing surface distal from the lead frame, and wherein the plurality of magnetic field sensing elements are supported by the first surface of the one or more substrates.

5. The current sensor of claim 1, wherein the at least one first magnetic field sensing element is vertically aligned with the external conductor and the at least one second magnetic field sensing element is not vertically aligned with the external conductor.

6. The current sensor of claim 2, wherein the die attach paddle comprises one or more slits, slots or apertures.

7. The current sensor of claim 2, wherein the plurality of leads are disposed at a first height with respect to the external conductor and the die attach paddle is disposed at a second height with respect to the external conductor, wherein the first height is different from and greater than the second height.

8. The current sensor of claim 2, further comprising a mold material enclosing the one or more substrates and a portion of the lead frame including the die attach paddle, and wherein a first plurality of the leads extend from a first side of the mold material and a second plurality of the leads extend from a second, opposite side of the mold material, and wherein the die attach paddle is attached to one or more of the first plurality of the leads and is spaced from the second plurality of leads.

9. The current sensor of claim 1, wherein the plurality of magnetic field sensing elements comprises at least one of a Hall effect element or a magnetoresistance element.

10. The current sensor of claim 9, wherein the magnetoresistance element comprises at least one of Indium Antimonide (InSb), a giant magnetoresistance (GMR) element,

an anisotropic magnetoresistance (AMR) element, a tunneling magnetoresistance (TMR) element or a magnetic tunnel junction (MTJ) element.

11. A current sensor for sensing a magnetic field generated by a current through an external conductor comprising:

a lead frame having a first surface and a second, opposing surface, a die attach paddle, a first plurality of leads and a second plurality of leads, the die attach paddle having first side adjacent to the first plurality of leads and second, opposing side adjacent to the second plurality of leads, wherein the first side of the die attach paddle is attached to at least one of the first plurality of leads and wherein the second side of the die attach paddle is spaced apart and electrically isolated from the second plurality of leads;

one or more substrates attached to the die attach paddle; and

a plurality of magnetic field sensing elements supported by the one or more substrates, wherein at least one first magnetic field sensing element of the plurality of magnetic field sensing elements is spaced from at least one second magnetic field sensing element of the plurality of magnetic field sensing elements such that the at least one first magnetic field sensing element is closer to the first side of the die attach paddle than to the second side of the die attach paddle and the at least one second magnetic field sensing element is closer to the second side of the die attach paddle than to the first side of the die attach paddle.

12. The current sensor of claim 11, wherein the one or more substrates have a first surface attached to the die attach paddle and a second, opposing surface, and wherein the plurality of magnetic field sensing elements are supported by the second surface of the one or more substrates.

13. The current sensor of claim 11, wherein the at least one first magnetic field sensing element is configured to generate a first magnetic field signal indicative of a distance between the at least one first magnetic field sensing element and the conductor and wherein the at least one second magnetic field sensing element is configured to generate a second magnetic field signal indicative of a distance between the at least one second magnetic field sensing element and the conductor, and wherein the current sensor further comprises a circuit responsive to the first magnetic field signal and to the second magnetic field signal and configured to generate a difference signal indicative of a difference between the first magnetic field signal and the second magnetic field signal, wherein the difference is indicative of the current carried by the conductor.

14. The current sensor of claim 11, wherein the at least one first magnetic field sensing element is vertically aligned with the conductor and the at least one second magnetic field sensing element is not vertically aligned with the conductor.

15. The current sensor of claim 11, wherein the die attach paddle comprises one or more slits, slots or apertures.

16. The current sensor of claim 11, wherein the first and second plurality of leads are disposed at a first height with respect to the conductor and the die attach paddle is disposed at a second height with respect to the conductor, wherein the first height is different from and greater than the second height.

17. The current sensor of claim 11, further comprising a mold material enclosing the one or more substrates and a portion of the lead frame including the die attach paddle, and wherein the first plurality of the leads extends from a first side of mold material and the second plurality of the leads extends from a second, opposite side of the mold material.

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18. The current sensor of claim 11, wherein the plurality of magnetic field sensing elements comprises at least one of a Hall effect element or a magnetoresistance element.

19. The current sensor of claim 18, wherein the magnetoresistance element comprises at least one of Indium Antimonide (InSb), a giant magnetoresistance (GMR) element, an anisotropic magnetoresistance (AMR) element, a tunneling magnetoresistance (TMR) element or a magnetic tunnel junction (MTJ) element.

20. A method for sensing a magnetic field generated by a current through an external conductor, the method comprising:

providing a lead frame having a first surface and a second, opposing surface, the lead frame comprising a die attach paddle and a plurality of leads, wherein one or more substrates are attached to the die attach paddle;

providing a current sensor comprising a plurality of magnetic field sensing elements supported by a surface of the one or more substrates, wherein at least one first magnetic field sensing element of the plurality of magnetic field sensing elements is spaced from at least one second magnetic field sensing element of the plurality of magnetic field sensing elements;

sensing the magnetic field by the at least one first magnetic field sensing element and the at least one second magnetic field sensing element, wherein the at least one first magnetic field sensing element and the at least one second magnetic field sensing element are orientated to sense the magnetic field in the same direction;

generating a first magnetic field signal indicative of a first distance between the at least one first magnetic field sensing element and an edge of the conductor;

generating a second magnetic field signal indicative of a second distance between the at least one second magnetic field sensing element and the edge of the conductor, wherein the second distance is different than the first distance; and

generating a difference signal indicative of a difference between the first magnetic field signal and the second magnetic field signal, wherein the difference is indicative of the current carried by the conductor.

21. The method of claim 20, further comprising positioning the at least one first magnetic field sensing element such that it is vertically aligned with the conductor and positioning the at least one second magnetic field sensing element such that it is not vertically aligned with the conductor.

22. The method of claim 20, further comprising forming one or more slits, slots or apertures in the die attach paddle.

23. The method of claim 20, further comprising disposing the plurality of leads at a first height with respect to the conductor and disposing the die attach paddle at a second

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height with respect to the conductor, wherein the first height is different from and greater than the second height.

24. The method of claim 20, further comprising enclosing the one or more substrates and a portion of the lead frame including the die attach paddle in a mold material, and wherein a first plurality of the leads extends from a first side of mold material and a second plurality of the leads extends from a second, opposite side of the mold material, and wherein the die attach paddle is attached to one or more of the first plurality of the leads and is spaced from the second plurality of leads.

25. The method of claim 20, wherein the plurality of magnetic field sensing elements comprises at least one of a Hall effect element or a magnetoresistance element.

26. The method of claim 25, wherein the magnetoresistance element comprises at least one of Indium Antimonide (InSb), a giant magnetoresistance (GMR) element, an anisotropic magnetoresistance (AMR) element, a tunneling magnetoresistance (TMR) element or a magnetic tunnel junction (MTJ) element.

27. A current sensor for sensing a magnetic field generated by a current through an external conductor, the magnetic field having a direction associated with a direction of the current through the conductor, comprising:

first means for sensing the magnetic field generated by the current to generate a first magnetic field signal indicative of a first distance between the first magnetic field sensing means and an edge of the conductor;

second means for sensing the magnetic field generated by the current to generate a second magnetic field signal indicative of a second distance between the second magnetic field sensing means and the edge of the conductor, wherein the second distance is different than the first distance;

means for supporting the first magnetic field sensing means and the second magnetic field sensing means in a spaced relationship, but with both the first and second magnetic field sensing means oriented to sense the magnetic field in the same direction; and

means for determining a difference between the first magnetic field signal and the second magnetic field signal, wherein the difference is indicative of the current through the conductor.

28. The current sensor of claim 27, wherein the first magnetic field sensing means is vertically aligned with the external conductor and the second magnetic field sensing means is not vertically aligned with the external conductor.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE
CERTIFICATE OF CORRECTION

PATENT NO. : 10,481,181 B2
APPLICATION NO. : 15/496152
DATED : November 19, 2019
INVENTOR(S) : Wade Bussing et al.

Page 1 of 1

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

In the Specification

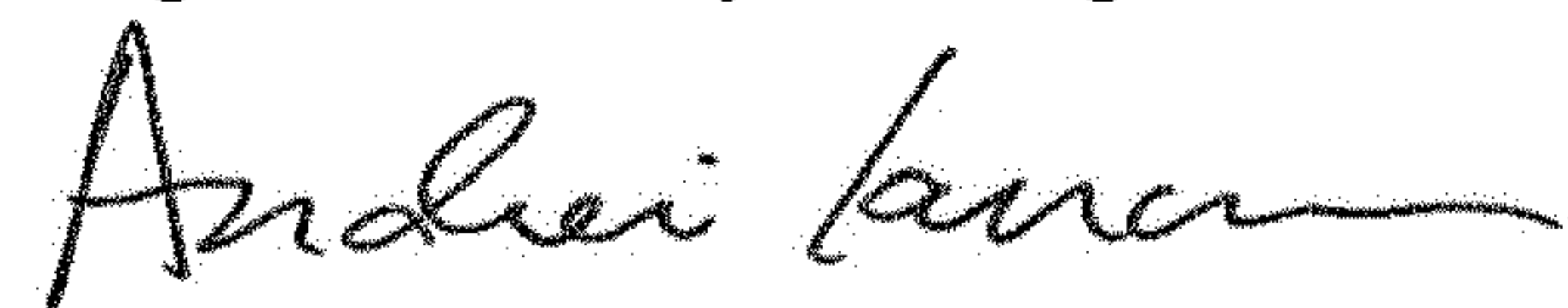
Column 2, Line 32 delete “conductor, than” and replace with --conductor than--.

Column 6, Line 43 delete “is it” and replace with --is--.

Column 9, Line 58 delete “carry” and replace with --carrying--.

Column 18, Line 31 delete “carry” and replace with --carrying--.

Signed and Sealed this
Eighteenth Day of August, 2020



Andrei Iancu
Director of the United States Patent and Trademark Office